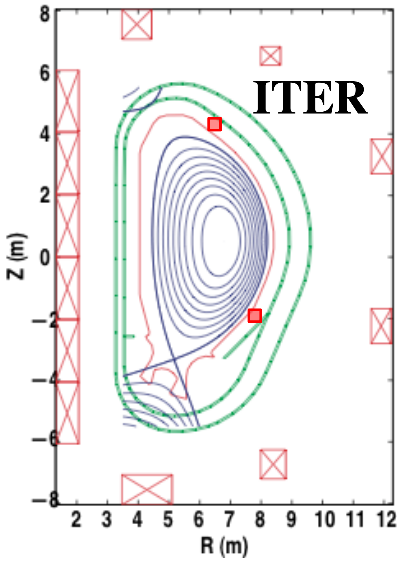
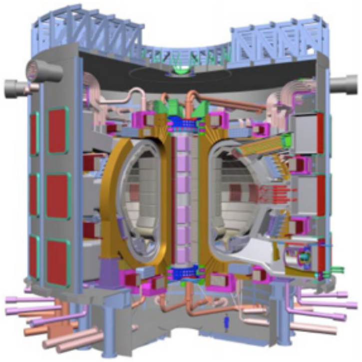
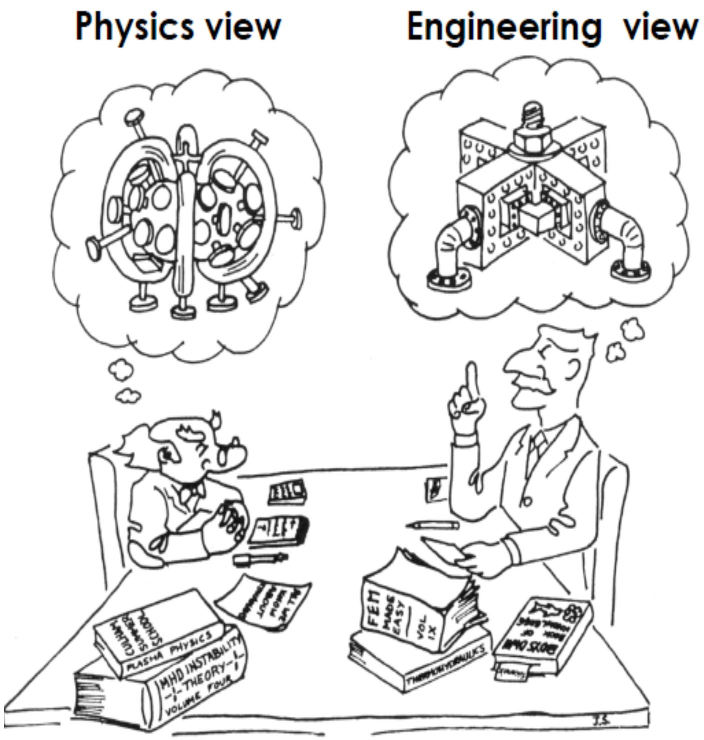
High Reliability Operation and Disruption Control in Tokamaks

D.A. Humphreys
General Atomics, San Diego, California







T. Todd, in R. Dendy Plasma Physics p. 448 (1993)

11th ITER International School
ITER Plasma Scenarios and Control
July 25-29, 2022

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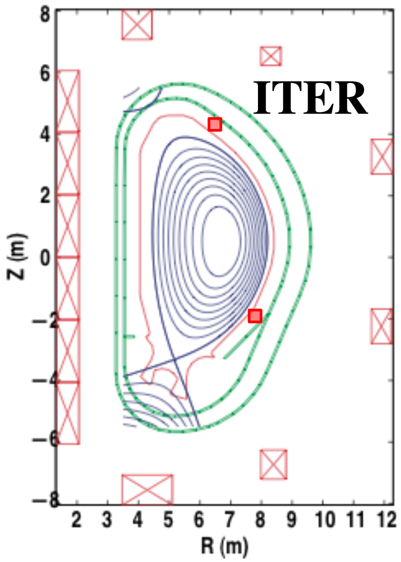

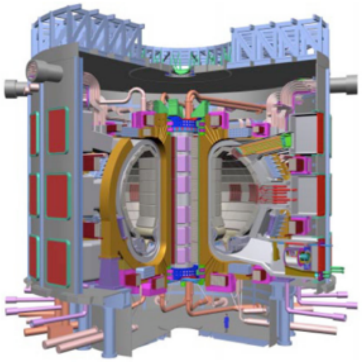

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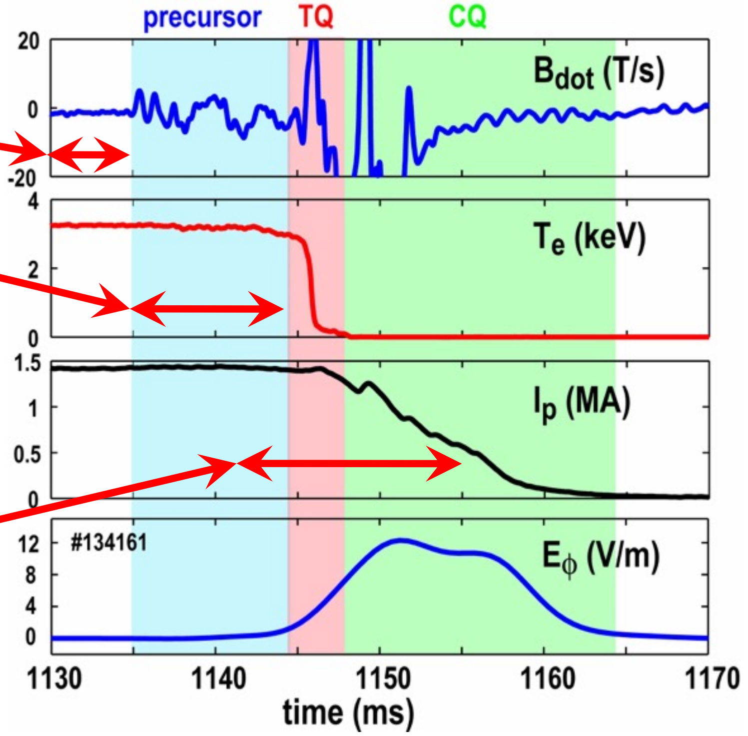
Physics view **Control design view**

T. Todd, in R. Dendy Plasma Physics p. 448 (1993)

Disruptions are Fault-Driven Plasma-Terminating Events that Can Damage Tokamaks and Reduce Operating Time

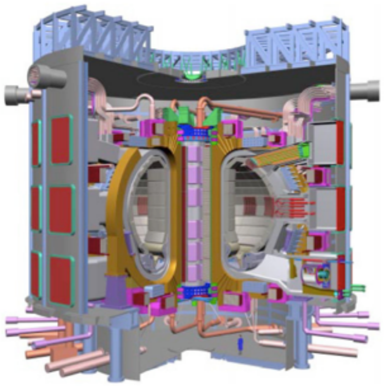
- Caused by some initial fault, e.g.:
  - Loss of operating resource (e.g. power supply, heating system, key diagnostic…)
  - Impurity influx
  - Loss of control
- Growth of uncontrollable condition, e.g.:
  - Vertical instability grows, plasma strikes wall
  - H-L transition or NTM/locked mode change plasma dynamics
  - Increased radiation exceeds heating capability
- Plasma instability thermal quench and resulting cold-plasma current quench:
  - Loop voltage cannot sustain current in highly resistive plasma
  - Runaway electron acceleration and beam

DIII-D Disruption time sequence



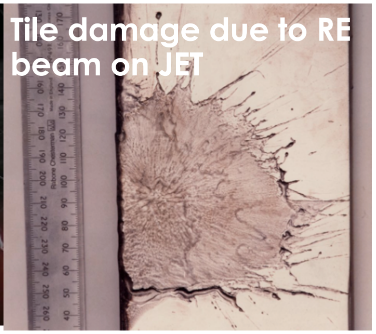
Success of ITER Requires Sufficiently Low Disruption Rate

- **Disruptions are fault-driven plasma-terminating events that can damage a tokamak and reduce operating time**
- **Mid-pulse disruptions eliminate planned discharge time following disruption, reducing physics productivity**
- **Disruptions may require long recovery time, reducing overall shot frequency**
- **Disruption heat fluxes can reduce component lifetime (e.g. divertor target ablation)**
- **Damage to in-vessel components can require shutdown for repair**



- Design target:
- <10% disruptivity

Tile broken by disruption forces in DIII-D



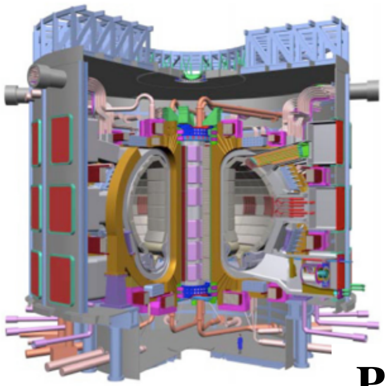
Tile damage due to RE beam on JET

Low to Zero Disruptivity with High Performance Depends on High Reliability Control in ITER and Fusion Power Plants

- **High Reliability:**
  - High probability of sustained operation
  - High availability (time fraction operating)
  - High confidence in design performance

- **High Performance:**
  - High values of physical performance metrics (beta, power output, efficiency, etc…)

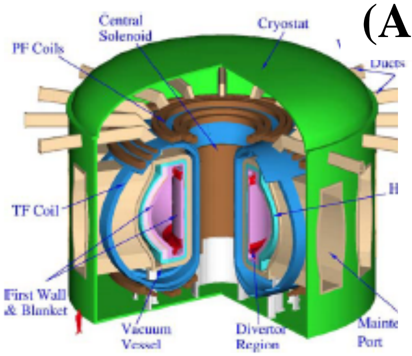
- **Both aspects depend critically on control:**
  - Design of controllers based on accurate models enables quantifiable reliability
  - Verification in simulations confirms implementation and function



ITER

- **Sufficiently high availability > 50%**
- **< 10% disruptivity**

Power Plant (ARIES-AT)



- **80% availability (out of full year)**
- **~ 0% disruptivity**

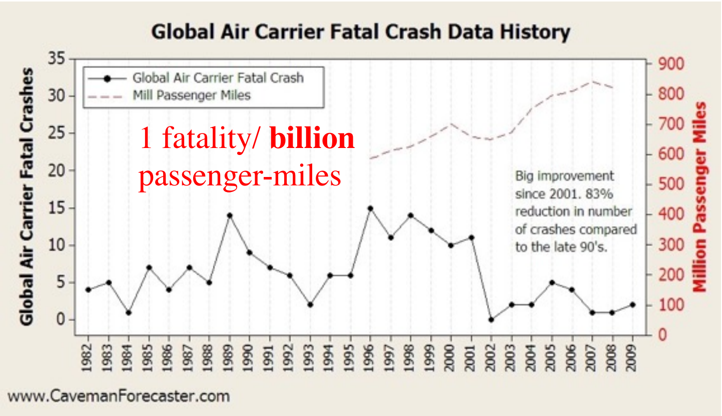
Najmabadi et al, FED 80 (2006) 3

Aircraft Control Provides a Good Example of High Reliability Control with High Performance

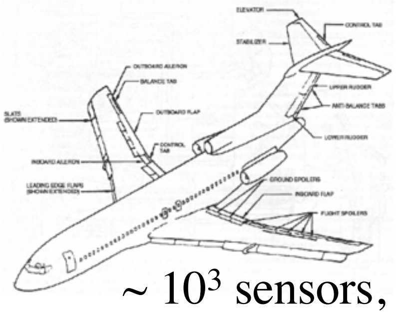
- **Commercial attractiveness requires high reliability:**
  - High availability needed for economics
  - High reliability (safety) required for passenger acceptance

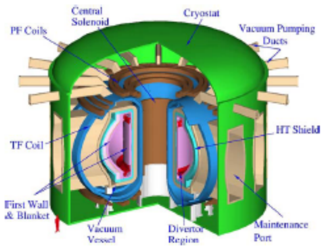
- **Missions of commercial/military aircraft demand high performance:**
  - High availability/reliability/efficiency
  - High maneuverability
  - High speed (in many cases)

- **Fusion power plants have comparable potential for reliability:**
  - Similar level of control complexity, requirements on performance… **Disruptivity < 10^{-10} – 10^{-9} /sec over years…**



www.CavemanForecaster.com





~ 10^3 sensors, 10^2 controlled parameters, 10^2 actuators

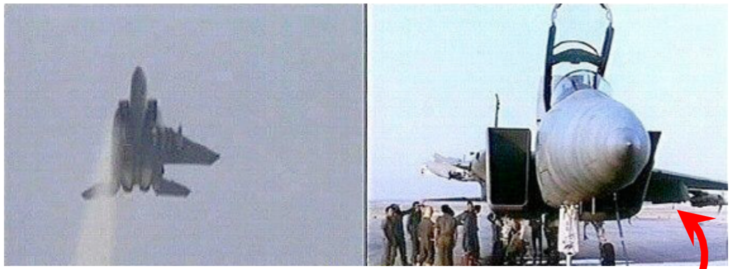
Najmabadi et al, FED <u>80</u> (2006) 3

High Performance Aircraft and Fusion Power Plants Require a High Degree of Robustness to Operate With Minimal Faults

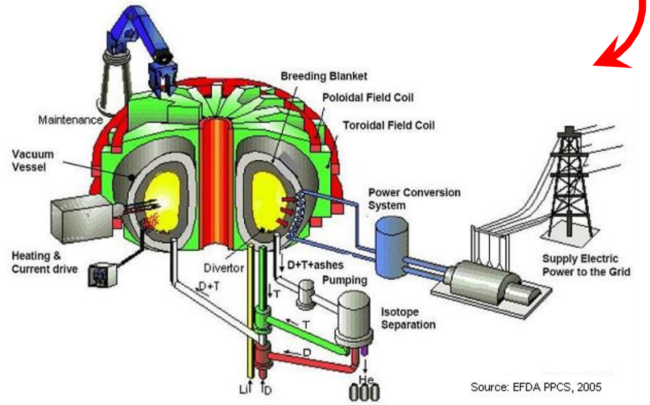
- **High performance aircraft:**
  - Intrinsically unstable (closed loop stable)
  - Operate near edge of performance envelope provided by technology
  - High speed, high airframe stress, high maneuverability…
  - High robustness to off-normal and even damage events!

- **High performance fusion power plant:**
  - Operates beyond many stability boundaries, depending heavily on robust active control
  - High plasma pressure, neutron fluence
  - Low incidence of lost-time faults
  - High robustness to off-normal events

Israeli Air Force F-15:



High performance, extreme robustness…



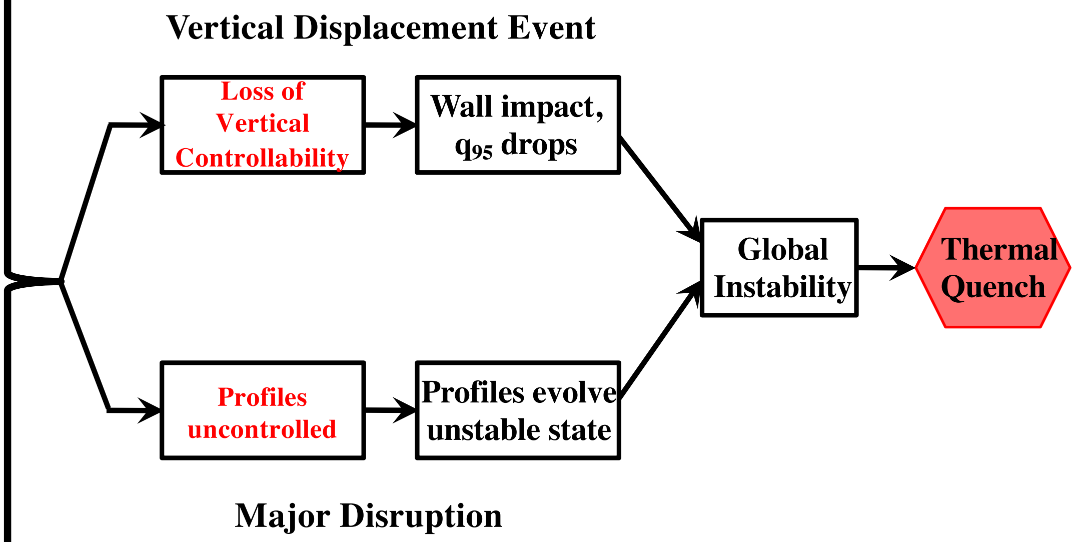
Source: EFDA PPCS, 2005

With thanks to the late T. Weaver, Boeing Corp.

Disruptions Are a Control Problem: Result of Insufficient Controllability of Operating Regime and/or System Faults

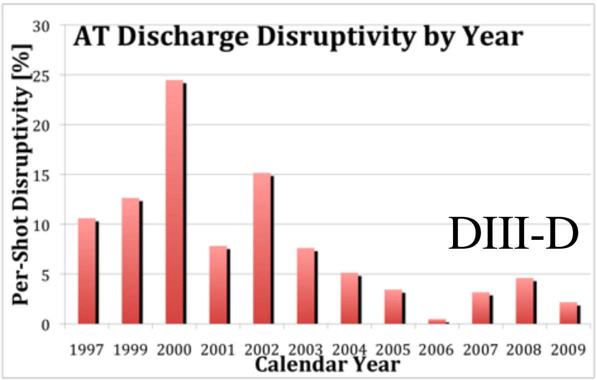
Primary Causes of Control Loss

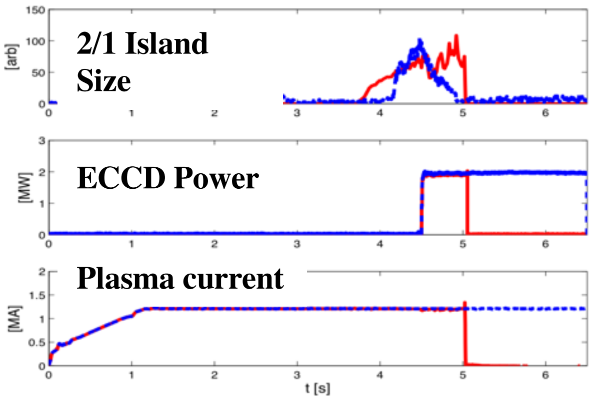
- Insufficient control capability for operating regime
- Design choice
- Hardware/system failure
- Human error
- Human intention



Improved Control Leads to Reduced Disruption Rate

- **JET disruptivity analysis [deVries, 2009]:**
    - "…lower disruption rates [over time]… primarily due to improvement in technical ability to operate JET"
- **DIII-D Steady-State Scenario disruption rate analysis 1997-2009:**
    - Experience, improved control reduces per-shot disruptivity from ~10-15% reduced to **<3%**
- **ECCD at rational surface controls NTM:**
    - Replaces missing bootstrap current or produces stable profiles
    - Prevents disruption
- **Improved vertical control prevents VDE:**
    - Routinely robust in operating devices
    - High confidence extrapolation to ITER design





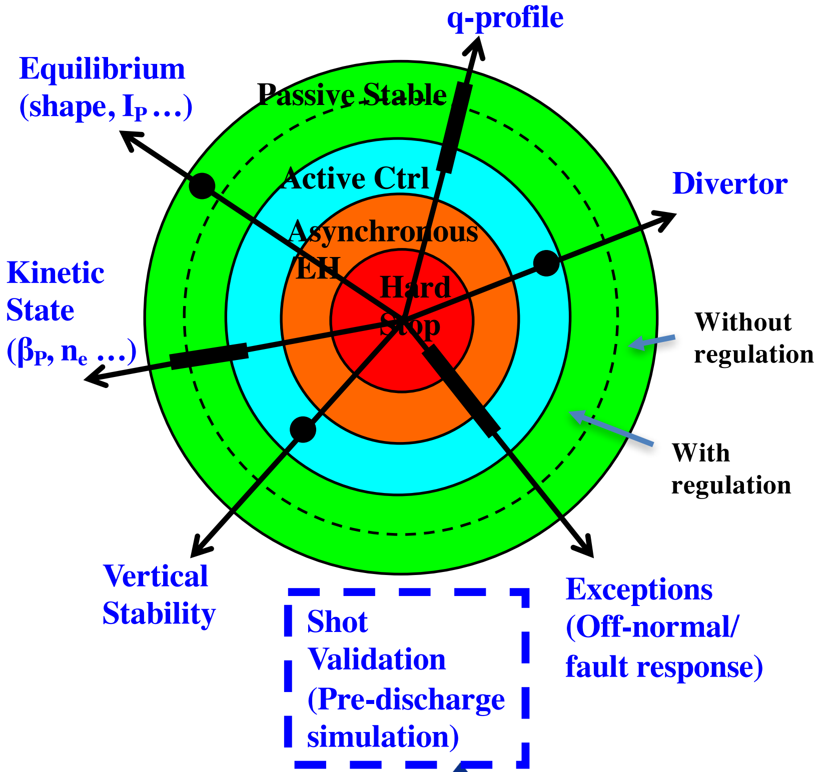
A Complete Control Solution is the Necessary and Sufficient Condition for Disruption-free Operation

- **Control of tokamak plasmas involves many different (somewhat) discrete control goals**

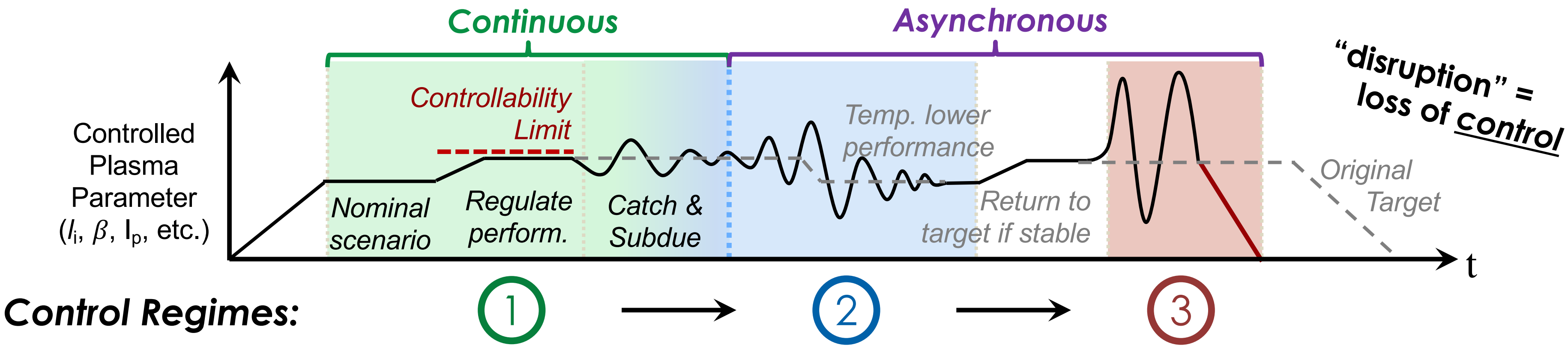
- **Different types of control fall into different Control Operating Regimes:**
  - Open-loop Passive Stable
  - Closed-loop Passive Stable
  - Actively Stabilized
  - Asynchronous Control

- **ITER has formalized approaches to off-normal/fault responses:**
  - Pre-discharge validation
  - Supervisory Monitoring
  - Exception Handling (EH)

Control Operating Regime Map



Control Solutions Act at Every Stage in Operating Space to Continuously Prevent or Asynchronously Avoid Disruptions



1. Continuous Prevention:

- Stable scenarios
- Regulate stability vs performance
- Mode Suppression
- ***Should prevent 99%+ of disruptions!***

2. Asynchronous Avoidance:

- Perturbative mode response, state-change
- Temporarily de-rate scenario, then return
- ***Should need to prevent < 0.9% disruptions!***

3. Emergency Avoidance:

Rapid Controlled shutdown:

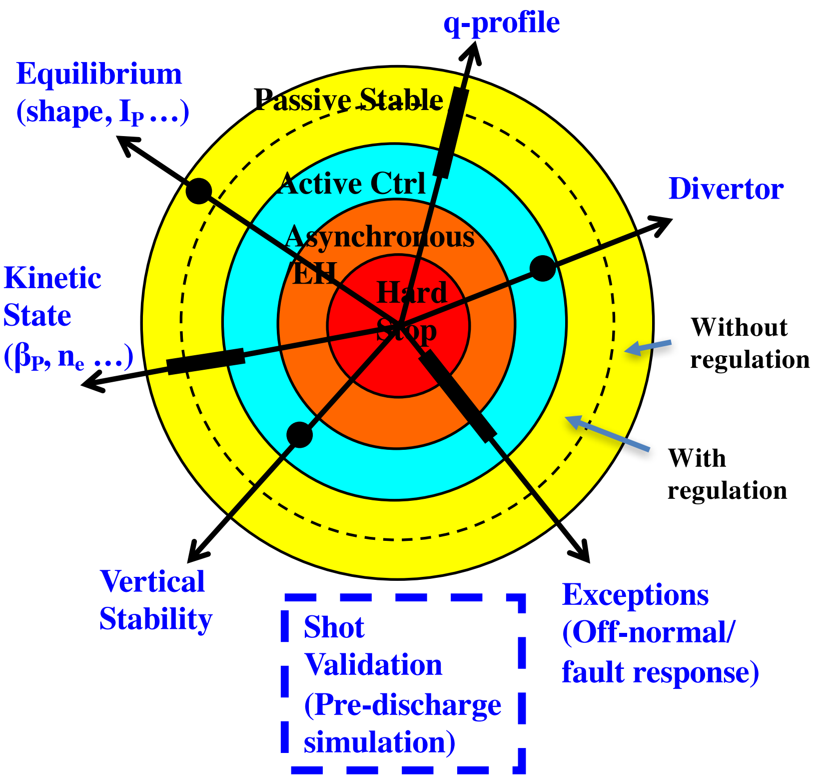
- Large piggyback study on DIII-D
- **< 0.09% disruptions!**

Mitigation should be the last resort:

- Has side-effects
- **< 0.01% disruptions!**

Continuous Control for Scenario:
Sequence of Plasma/System States… WHAT We Want the Tokamak to Do

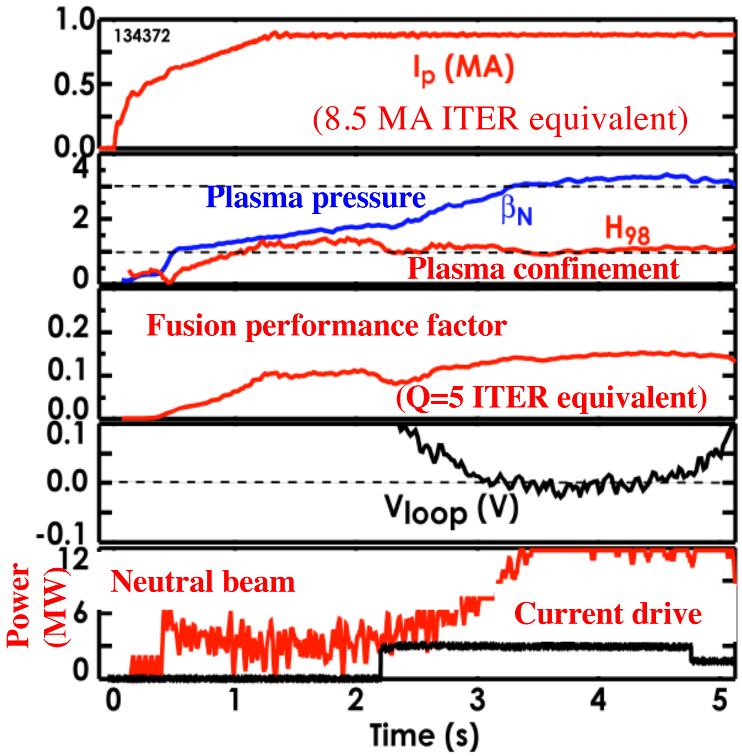
Control Operating Regime Map



Shot
Validation
(Pre-discharge
simulation)

Physics Interpretation of “Scenario” Includes Plasma Regime and Use of Actuators = “What the Scenario Is”

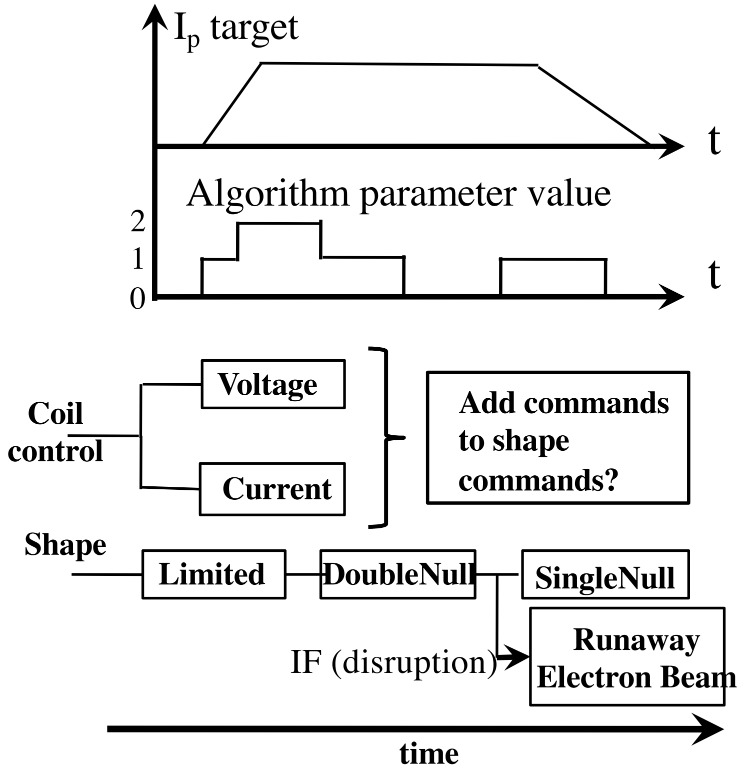
- **“Scenario” has different meaning to different communities:**
  - Physics scenario vs control scenario
- **Plasma regimes:**
  - Key plasma characteristics…
  - Confinement, profiles, stability to various instabilities or proximity to stability boundaries
  - (Reactor) Burn state, fusion gain, thermal stability properties
- **Use of Actuators:**
  - Sequence of application for access to regime (avoid instability boundaries, establish profiles, etc…)
  - Application to sustain regime (sustain profiles, etc…)



Doyle et al, IAEA 2008

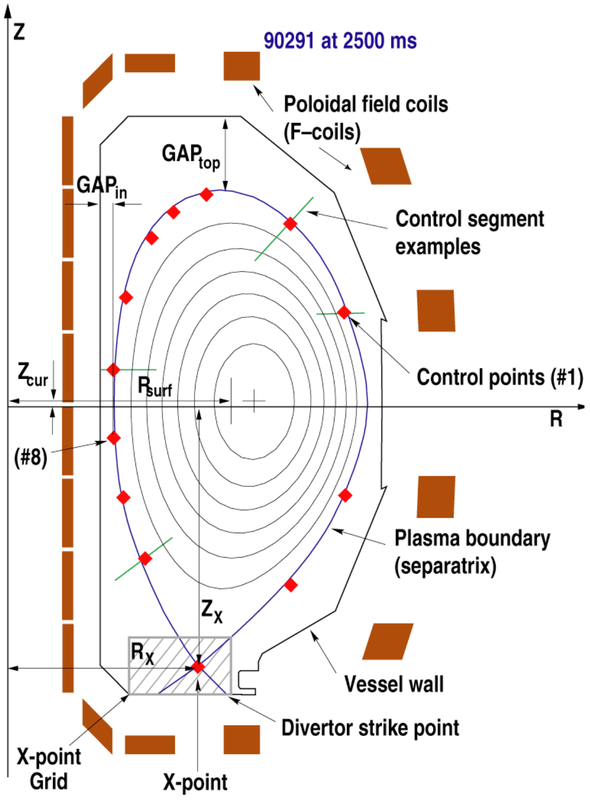
Control Interpretation of “Scenario” Includes Target Waveforms and Feedback Algorithms = “How the Scenario is Accomplished”

- **Feedforward target waveforms**
  - Related to use of actuators, but actual waveforms of interest for control
- **Choice of feedback algorithms:**
  - What types of control algorithms
  - Choice of controlled variables, how algorithms interact
- **Programmed vs Asynchronous switching (of regimes/algorithms)**
  - Gain scheduled vs robust algorithms
  - Possibility of change in plasma regime



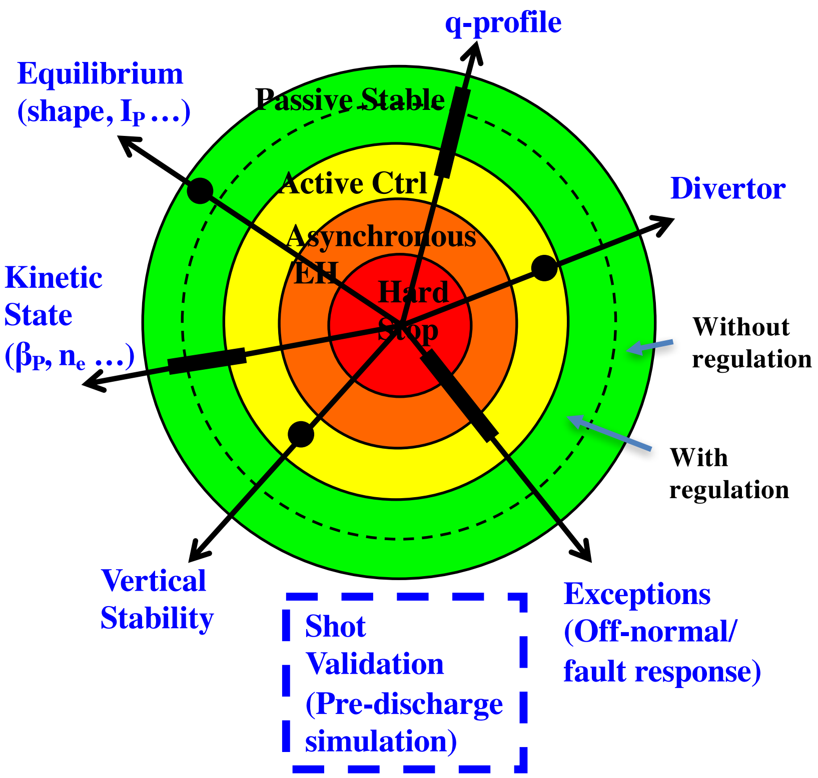
Nominal Continuous Control Acts (Continuously) to Produce the Desired Scenario Robustly

- **Equilibrium/Boundary Control**
- **Divertor detachment**
- **Profile control**
- **Tearing mode stabilization**
- **Generally, continuous algorithms are designed to be robust to expected noise/disturbances/ uncertainties without changing gains, BUT can also change controllers as scenario evolves…**



Robust Active Control for Stabilization of Key Modes

Control Operating Regime Map

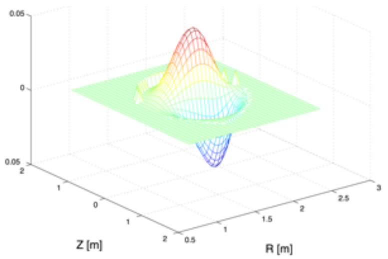


Example of Active Stabilization: Vertical Instability Characterized by Unstable Vertical Growth Rate γ_Z

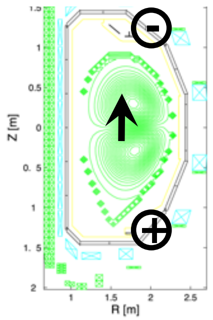
- **Vertical instability is n=0 (axisymmetric):**
  - Vertical plasma motion typically ~rigid
  - Motion induces currents in conductors (wall and coils) that slow mode growth
  - Linear dynamic equations are derived from force balance on plasma and Faraday's law circuit equations

- **Basic control representation is similar to inverted pendulum:**
  - Single unstable mode (γ_Z), single power supply mode (γ_{PS})
  - ALSO a conductor mode corresponding to penetration rate through wall (γ_V)

Perturbed Current Density



Plasma Motion, Induced Current

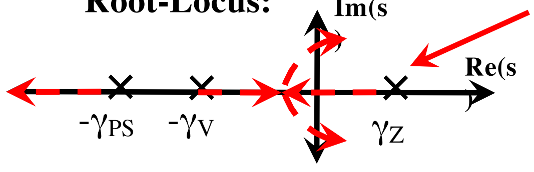


Vessel Flux Change from Plasma Motion

$$M_{VV}\dot{I}_V + R_{VV}I_V + \boxed{\frac{\partial \psi_{PV}}{\partial Z_P}\dot{Z}_P} = 0 \Rightarrow \underbrace{\dot{I}_V = AI_V}$$

Solution: many eigenmodes, one unstable (γ_Z)

Root-Locus:



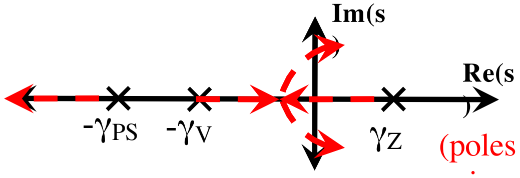
(increasing gain…)

Stabilizing the Vertical Instability Depends on Plasma, Conductor, and Power Supply Characteristics

- **Root-locus shows rough requirements for stabilization:**
  - Like inverted pendulum: power supply response bandwidth (γ_{PS}) sufficiently larger than γ_Z
  - Vessel penetration rate sufficiently large relative to growth rate
  - Actual dynamic response more complex…
  - Thick vessel or In-vessel passive structure produces system “zeros” that can require velocity feedback

- **Nonideal characteristics limit control capability significantly:**
  - Voltage saturation limits effectiveness of high gain…

Root-Locus:



(poles move with increasing gain…)

Root-locus interpretation: centroid of poles constant as gain increases…

➔ Once $\gamma_{PS} >> \gamma_Z$ stability depends on sufficiently large γ_V/γ_Z

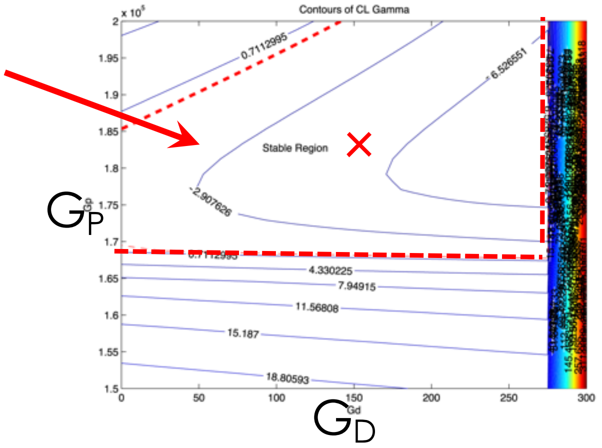
➔ Larger γ_V moves centroid to left, improves ability to stabilize…

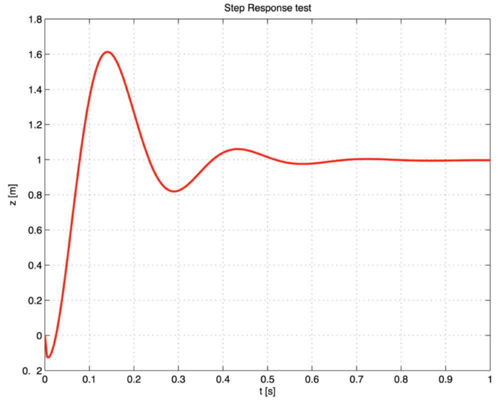
Stability margin: $m_s \approx \dfrac{\gamma_V}{\gamma_Z}$

➔ Measure of gain (voltage) needed to stabilize and robustness of stabilization

Example of Robust Design with PID: Large Stable Gain Space

- **Single variable PID control lends itself to brute-force scan of gains:**
  - Sweep proportional gain (G_p) and derivative gain (G_d)
  - Typically select center of stable region for maximum robustness
  - Tradeoff with response/settling time performance…
- **Designing for large stable gain space:**
  - Increases probability of stable performance
  - Tolerant to uncertainties in most system aspects
  - Does not directly address noise and disturbance effects, or many nonlinearities…

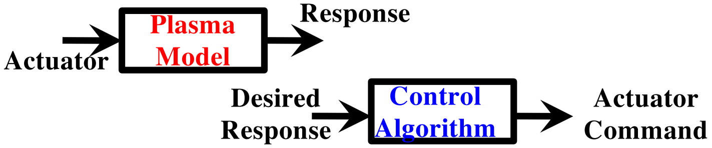


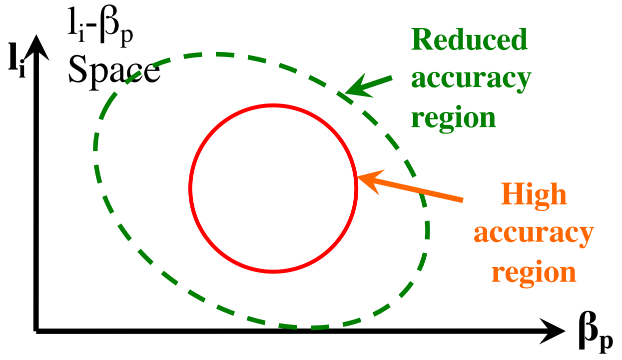


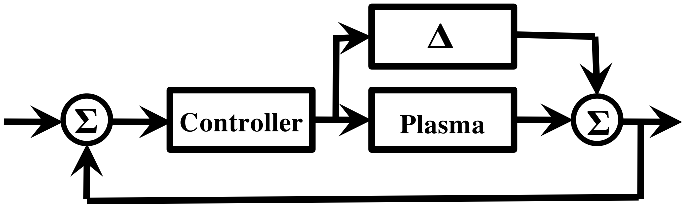
Robust Control Requires Sufficiently Accurate Models But Can Provide Good Performance in Wide Region of Control Operating Space

- **Design of algorithms requires models:**
  - Model describes response of system to actuators
  - Control algorithm "inverts" model to derive actuator command needed for desired system response…

- **Robust design methods can handle some degree of inaccuracy in models:**
  - Design controller to guarantee stability with specified uncertainty **Δ**
  - Greater uncertainty requires higher cost for actuators
  - Can also treat model error as disturbance

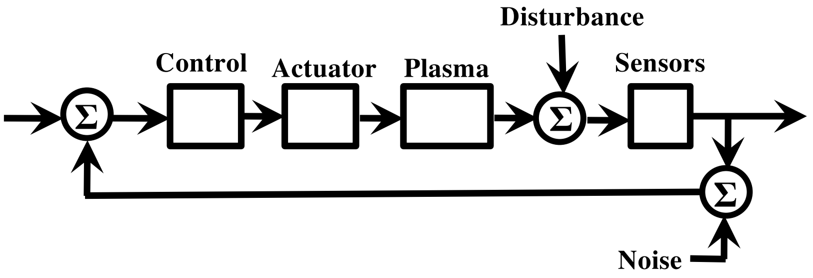


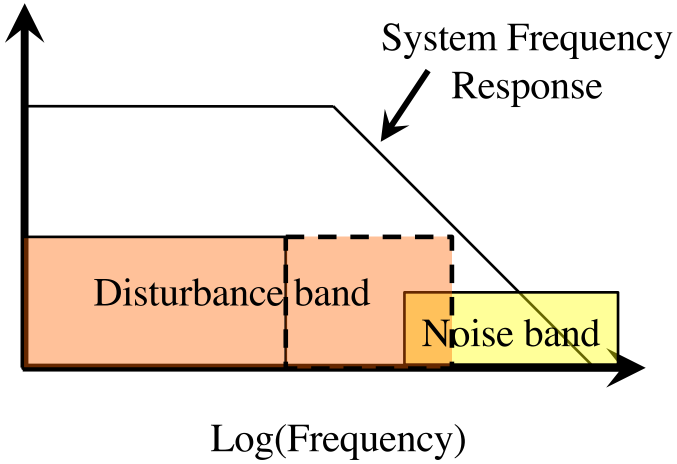




High Performance Control Requires Good Noise and Disturbance Rejection

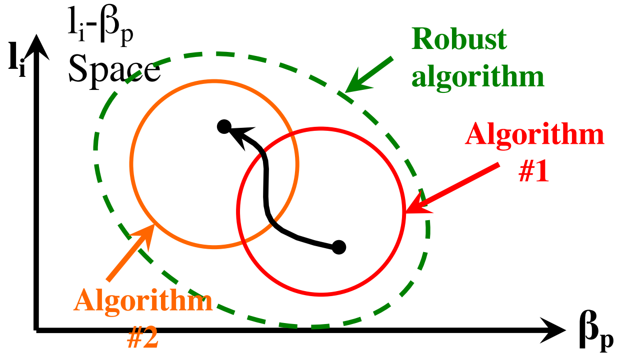
- **High performance:**
  - High accuracy in matching command
  - Good dynamic response: small levels of fluctuation, small overshoots…
- **Noise rejection:**
  - Don't respond to noise signals (typically high frequency, but not always…)
- **Disturbance rejection:**
  - Respond to disturbance so as to suppress (typically lower frequency than noise, but not always…)
  - If frequencies overlap, must discriminate in other ways, e.g. mode discrimination, Poisson (√N) reduction

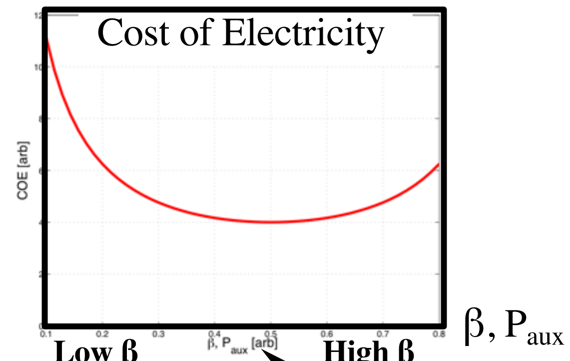




Control Designers are Faced with Many Choices and Tradeoffs for Robustness

- **Gain scheduling vs robust:**
  - Switch from **algorithm #1** to **algorithm #2** based on changes in plasma state (“gain scheduling”)?
  - Use **single robust algorithm** over large operating space?
- **Where to use each with what balance:**
  - High accuracy often requires accurate models, gain scheduled multiple algorithms (e.g. vertical stability)
  - Control with intrinsic uncertainty often requires use of robust, lower accuracy algorithms (e.g. NTM suppression)
  - Power plant: balance cost of high control (actuator) capability vs need for high plasma performance
- **Scenarios: what regimes to operate in?**

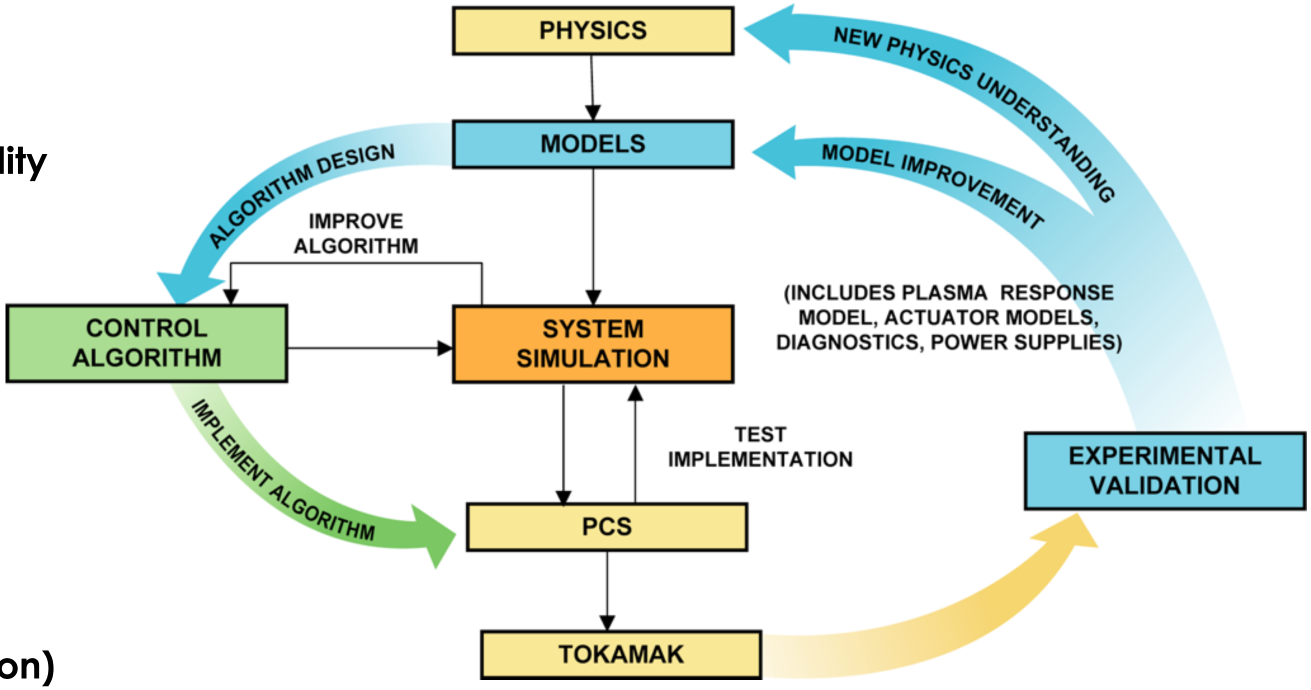




Low β
Low actuator cost
→
High β
High actuator cost

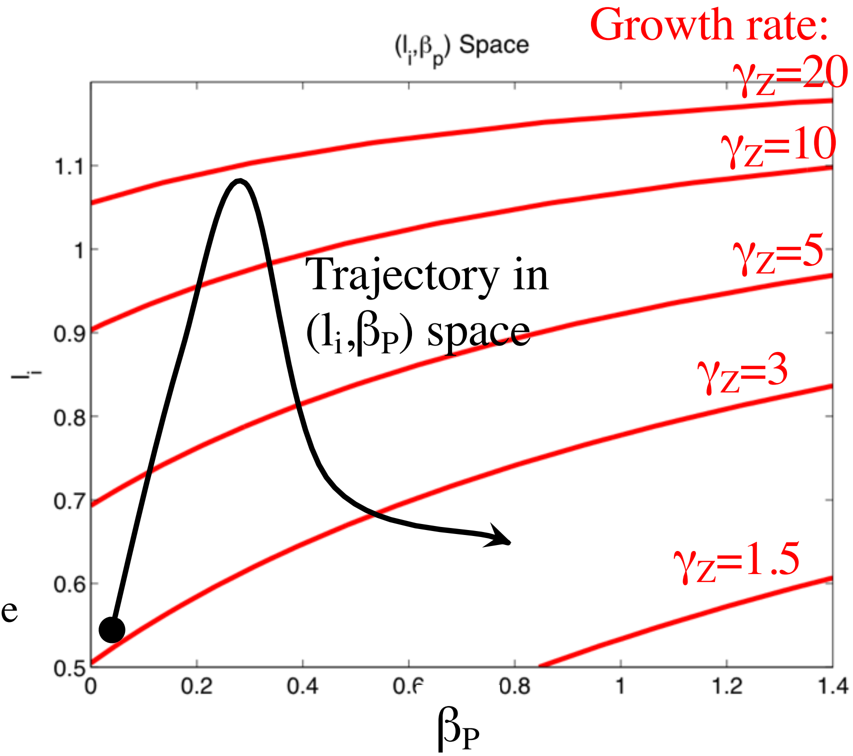
In General High Performance, High Reliability Control Requires Systematic Model-Based Design

- Control-level models
- Quantified region of validity and uncertainty
- Verification of controller implementation in simulations before use
- “Validation” (quantification) of performance before use



Control Operating Space: Unifying Physics and Control Scenarios with Control Performance Metric (γ_Z) Enables Quantified Risk and Reliability

- **Superimposing control requirements on physics scenario:**
  - Trajectory shows variation in **vertical growth rate** in (l_i, β_P) space as ITER discharge scenario evolves in time
  - Growth rate that must be stabilized peaks in mid-scenario
  - Maximum control demand sets requirement on control system capabilities…



l_i = measure of internal inductance (peaking of current distribution)

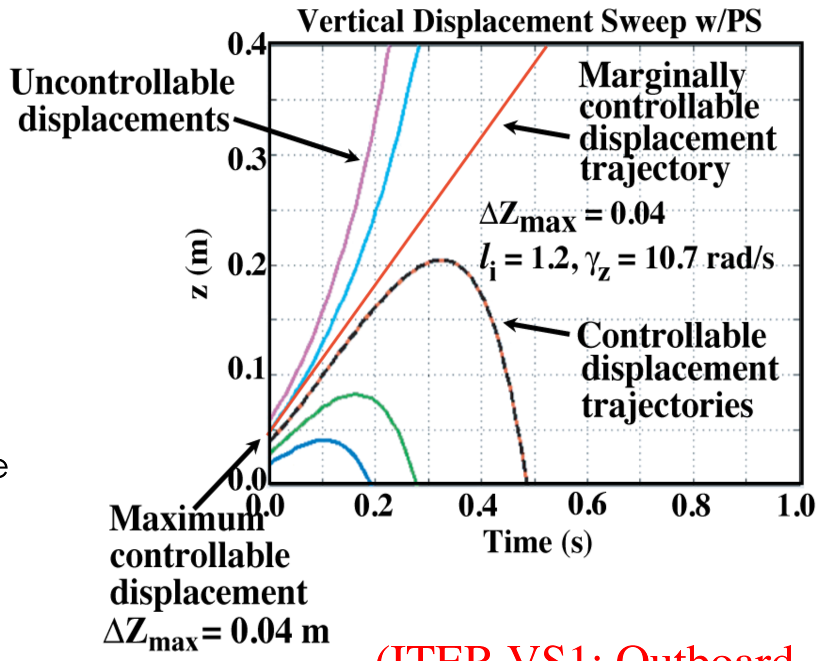
β_P = measure of plasma pressure

Vertical Controllability Quantified by Maximum Controllable Displacement ΔZ_{MAX}

- **Many disturbances result in sudden jump in vertical position Z_P:**
  - ELM: rapid loss of edge current shifts current centroid
  - Tearing mode: growth of island shifts current centroid
  - Must design to reject ΔZ_P expected

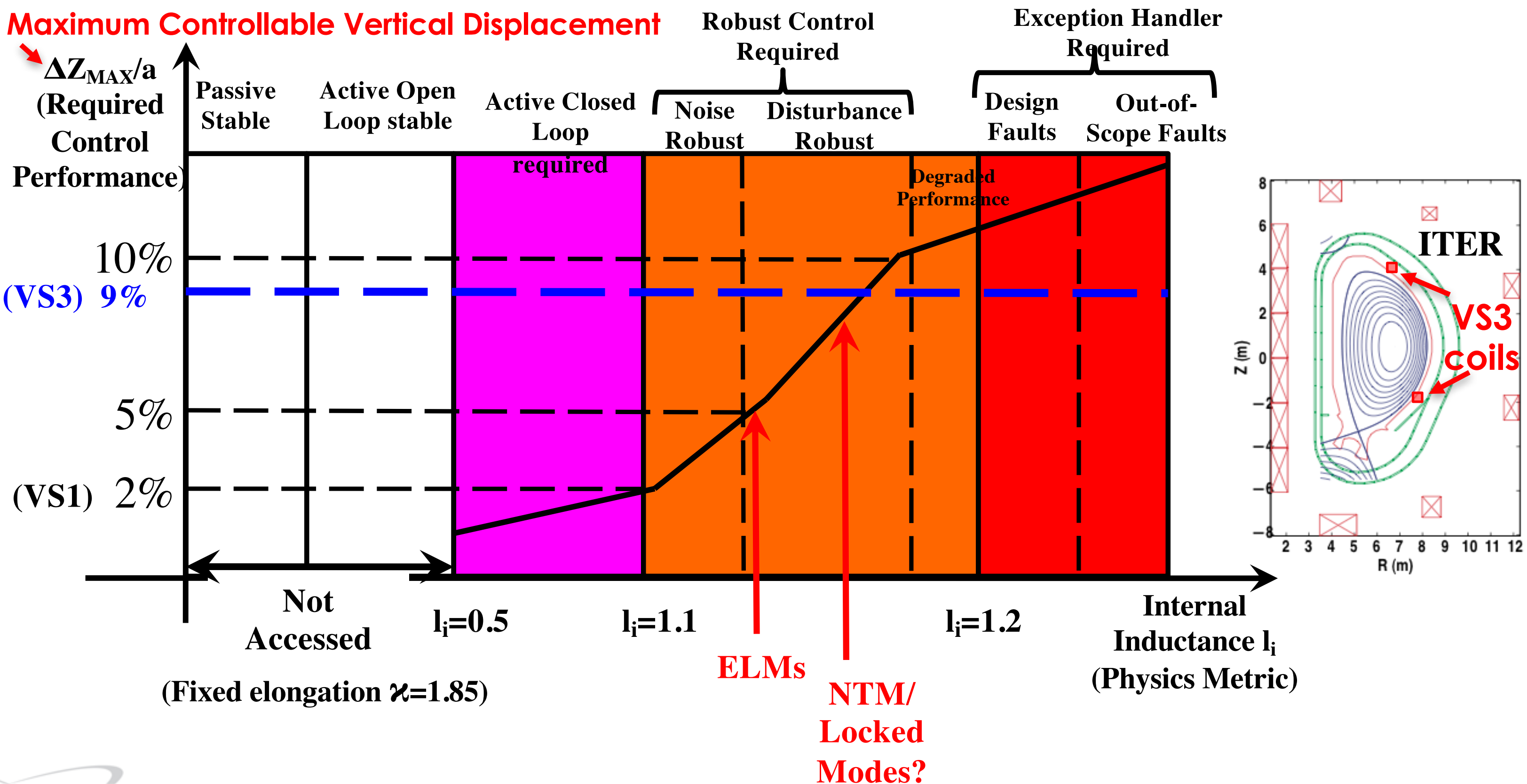
- **Maximum controllable displacement is useful metric to quantify robust control:**
  - ΔZ_{MAX} = maximum ΔZ_P beyond which motion can't be reversed with saturated voltage (reflects γ_{PS}, current limit,…)
  - Measure of "best possible"
  - $\Delta Z_{MAX}/a$ is machine-independent metric

Example of Analysis and Gedanken Experiment to Calculate ΔZ_{max}



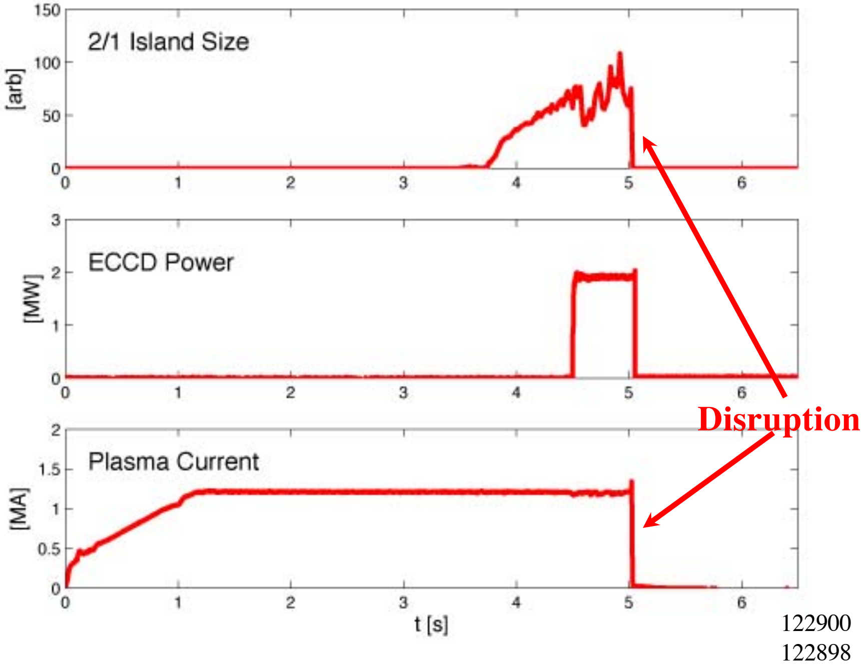
(ITER VS1: Outboard PF coils only)

Control Operating Space for ΔZ_{MAX} Performance in ITER Quantifies Robustness to Disturbances



Tokamaks Operating in High Performance (high β) Can Be Unstable to Neoclassical Tearing Mode-Driven Magnetic Islands

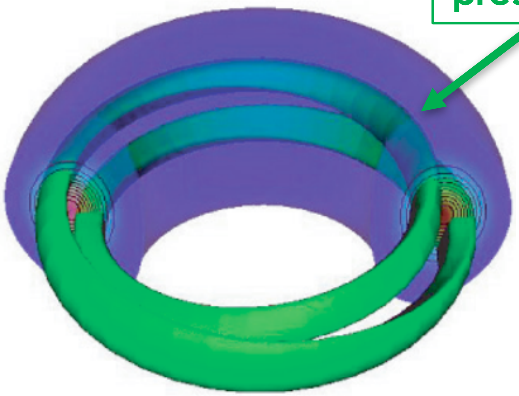
2/1 NTM can disrupt plasma if not stabilized



m/n=2/1 NTM:

Poloidal periodicity = 2
Toroidal periodicity = 1

Lost bootstrap current and pressure

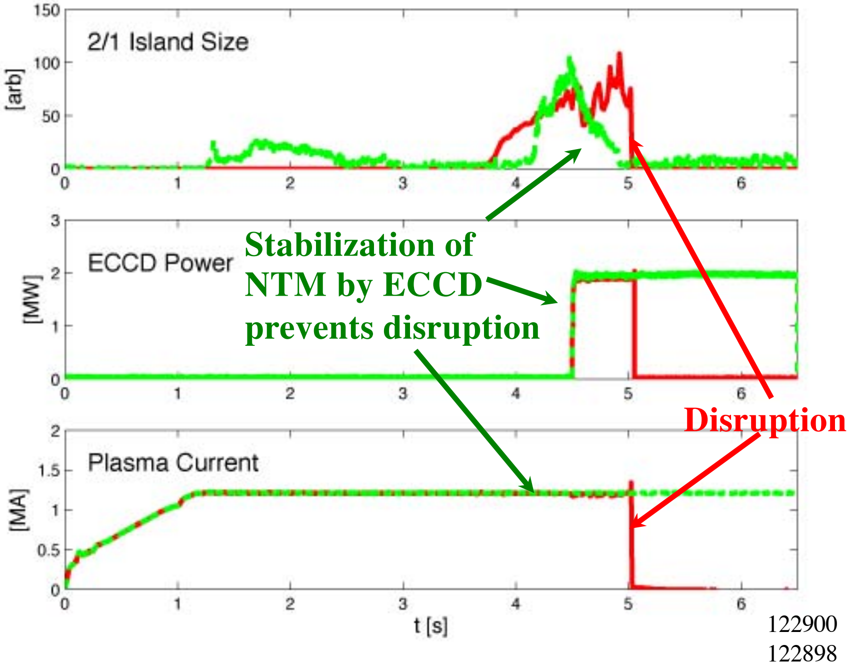


NIMROD
Non-Ideal MHD with Rotation
Open Discussion Project

Figure courtesy of D. Brennan

Electron Cyclotron Current Drive (ECCD) Can Stabilize the Neoclassical Tearing Mode With Enough Heating/Current Drive Efficiency and Good Alignment

2/1 NTM can disrupt plasma if not stabilized

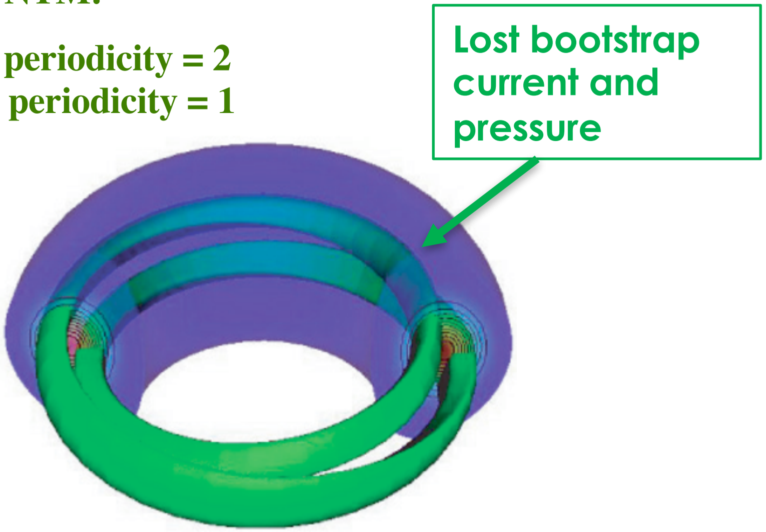


Stabilization of NTM by ECCD prevents disruption

Disruption

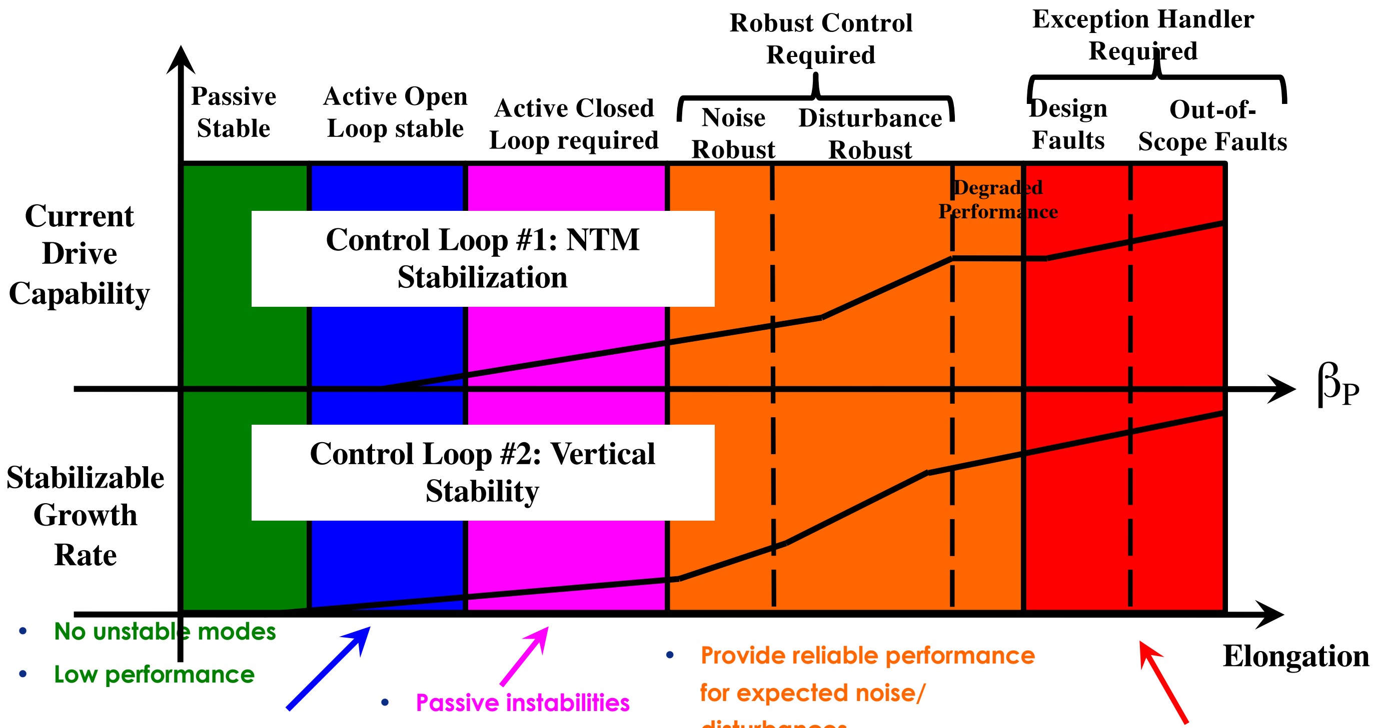
m/n=2/1 NTM:

Poloidal periodicity = 2
Toroidal periodicity = 1



Lost bootstrap current and pressure

Control Operating Space Can Be Used to Assess and Specify Performance Needed for Many Control Loops



- No unstable modes
- Low performance

- Open loop actuators produce stable regimes

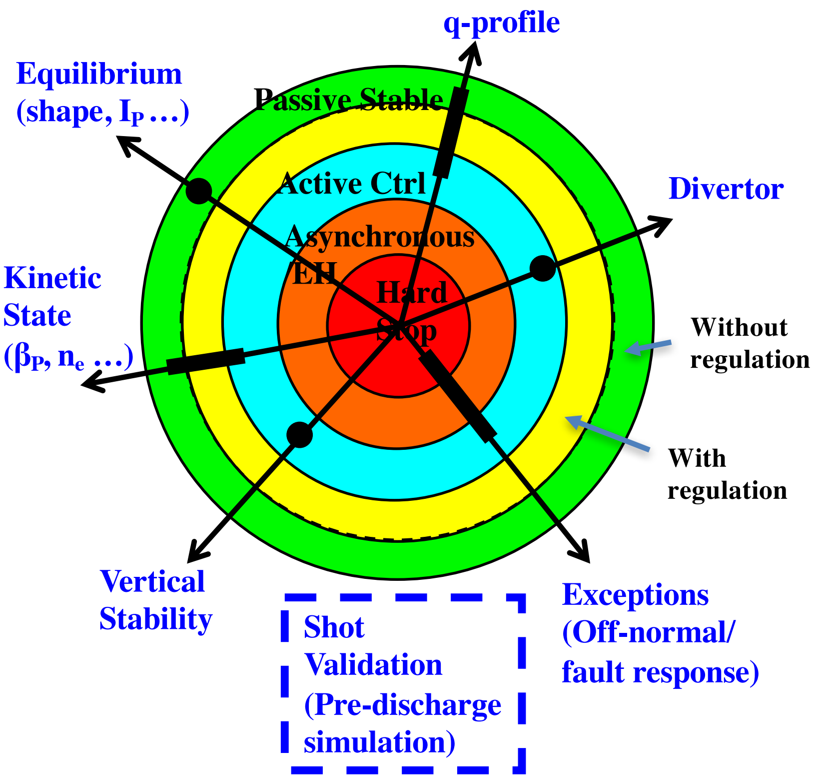
- Passive instabilities
- Stabilize by active closed loop feedback

- Provide reliable performance for expected noise/ disturbances

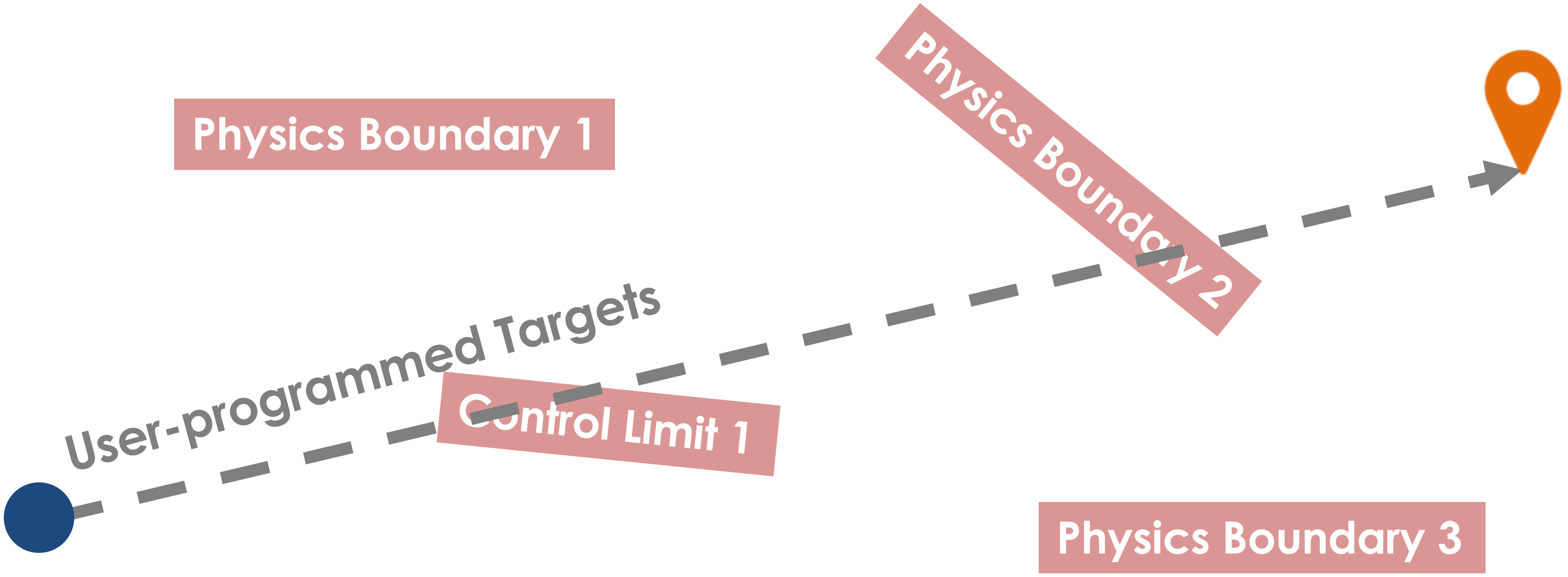
- Design responses to envisioned faults and detectable exception events

Continuous PROXIMITY Control for Scenario to PREVENT Disruption: Active Regulation of Proximity to Controllability/Stability Boundaries

Control Operating Regime Map

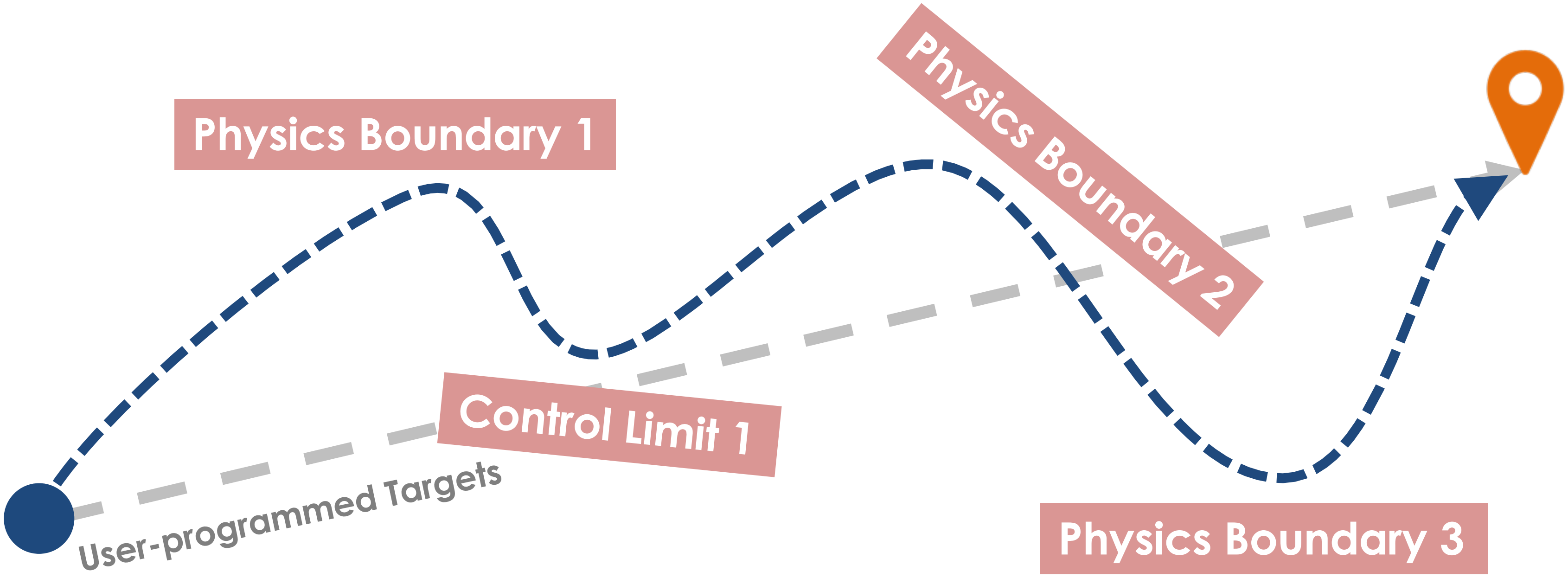


Comprehensive disruption prevention must cover the full range of control regimes



- ***Proximity control:*** *continuous monitoring and adjustment of targets away from stability/control limits*

Comprehensive disruption prevention must cover the full range of control regimes



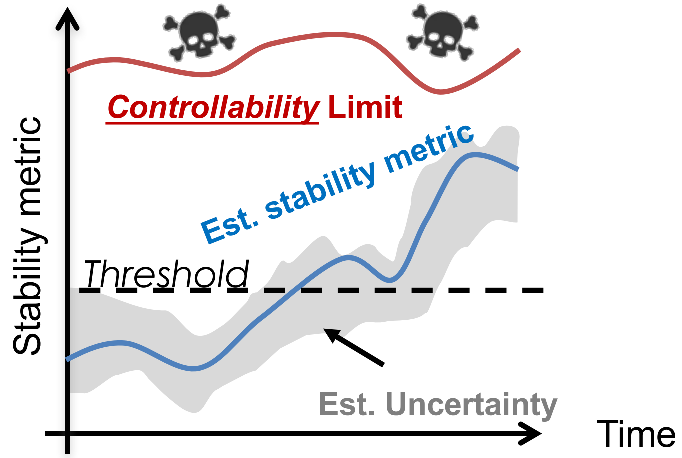
- ***Proximity control:*** *continuous monitoring and adjustment of targets away from stability/control limits*

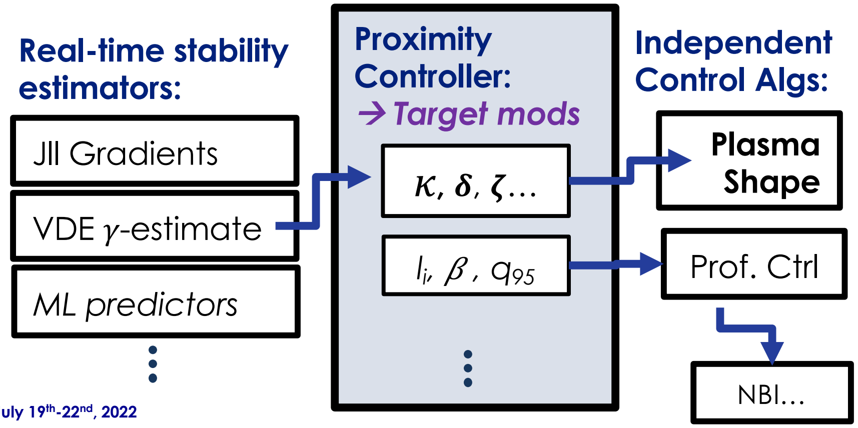
Quantified Controllability Metrics Enable Continuous Regulation of Proximity-to-instability to Prevent Disruption

- **Continuous prevention is the first defense against disruption…**

  and the least developed!
  - Controlling proximity to known instability limits is key for continuous prevention

- **Proximity control: *continuously regulate nearness to instability***
  - Maps live stability-calcs to plasma parameters targets, adjusting in RT
  - Generalized architecture on DIII-D for parallel application of multiple proximity regulation algorithms





Real-time stability estimators:

J∥ Gradients

VDE γ-estimate

ML predictors

⋮

Proximity Controller:
→ Target mods

$\kappa, \delta, \zeta\ldots$

l_i, β, q_{95}

⋮

Independent Control Algs:

Plasma Shape

Prof. Ctrl

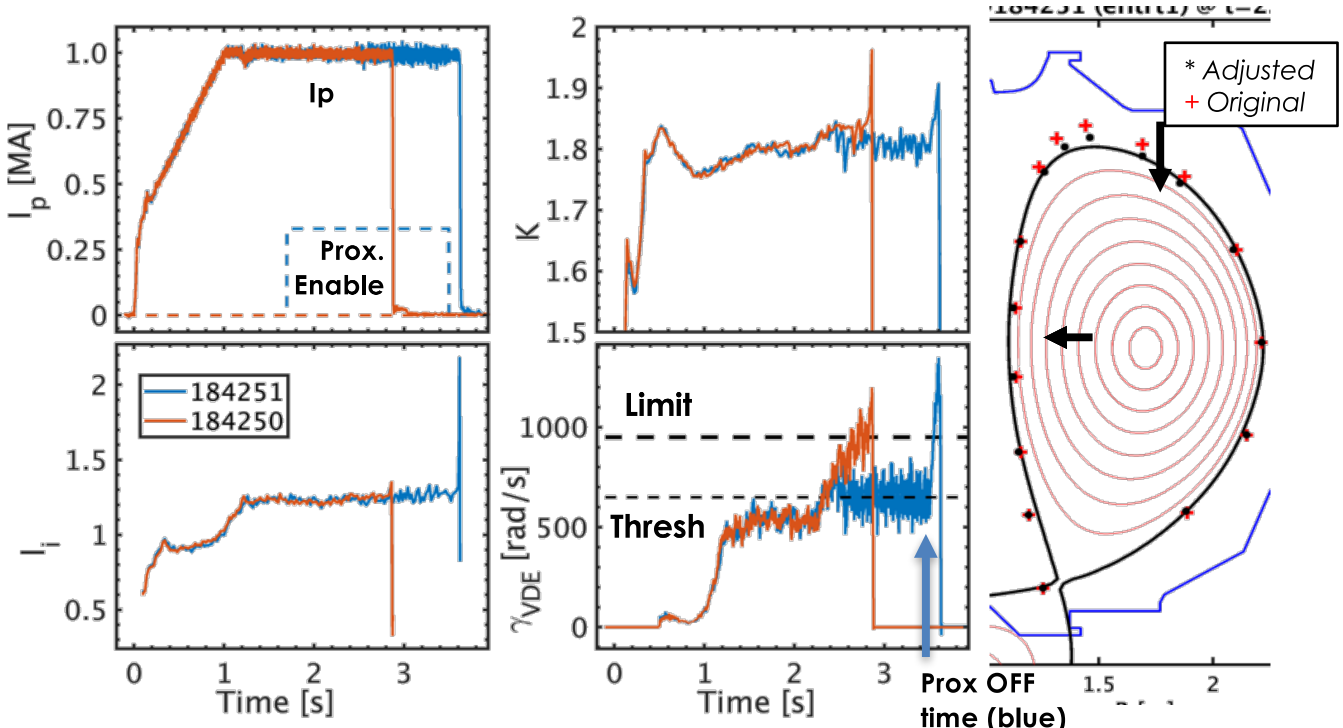
NBI…

Proximity Controller with Realtime γ_z Calculation Successfully Prevents VDEs

- **VDE reliably prevented until Proximity Controller intentionally disabled**

Red:
No Prox Ctrl
Pre-shot K-target
ramp to VDE

Blue:
Prox Ctrl on
1.75-3.5s
Prox. control when
γ>threshold:
reduces *K*,
inner-gap

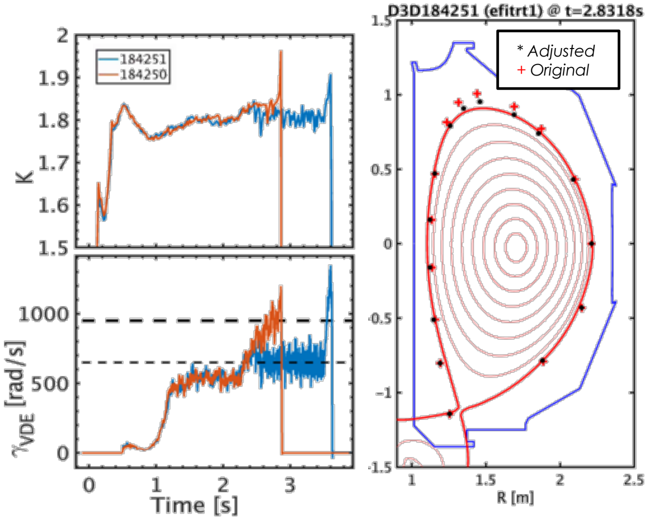


Prox OFF time (blue)

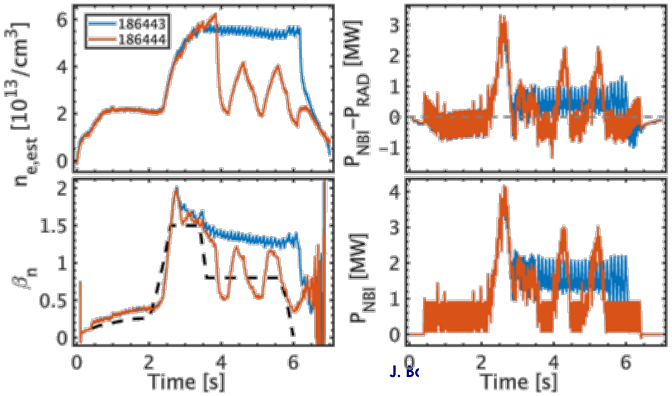
[1] J.L. Barr 2021 NF [2] E. Olofsson 2022 PPCF [3] B. Sammuli 2021 FED

Proximity control is being applied to a wide array of disruption prevention problems

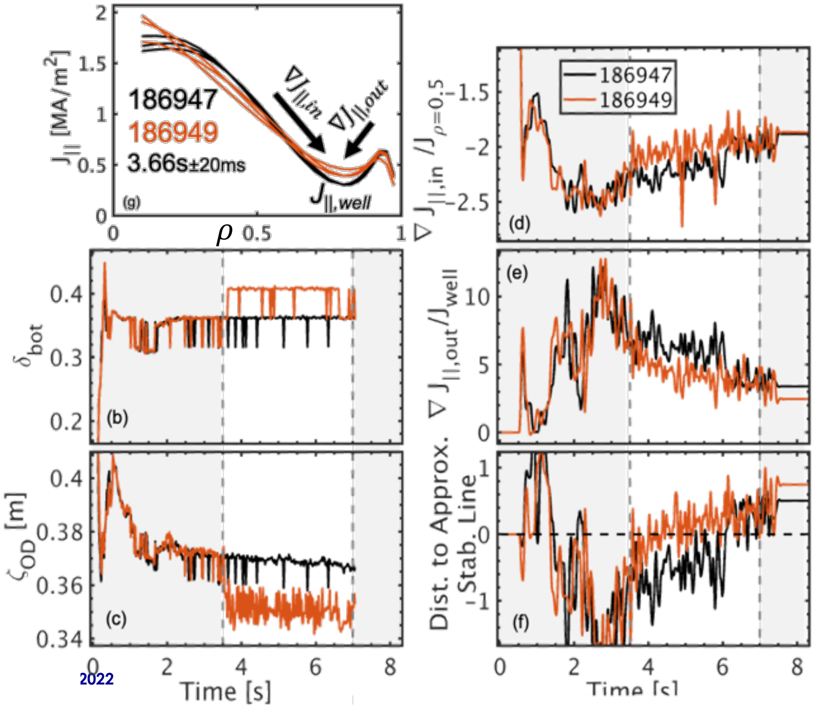
- **Robust VDE prevention**



- **H-L Back-Transition prevention**

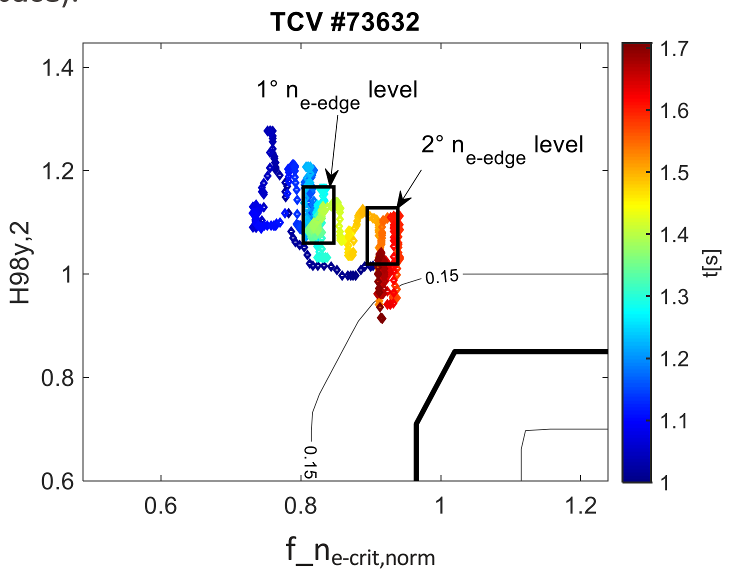


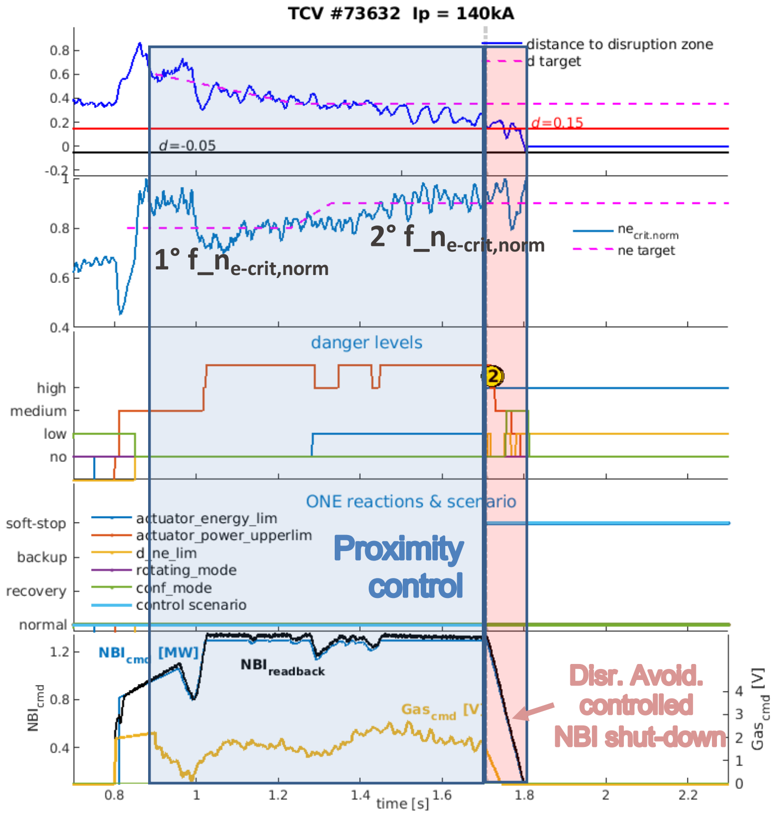
- **Control to maintain stable $J_{||}$-“well” TM stability metric**



H-mode Density Limit with proximity control on TCV

- Definition of **stability** and **controllability** boundaries and integration of **continuous prevention** with **exception & off-normal events handling** (asynchronous response).
  - **PI controllers** on **$f\_n_{e\text{-crit-norm}}$** (scaling for $n_{e\text{-edge}}$ normalized wrt $n_{e\text{-edge-crit}}$) & **$d_{H98y,2\text{-}f\_n_{e\text{-crit,norm}}}$** (distance from empirical disruptive boundary in the **state space**).



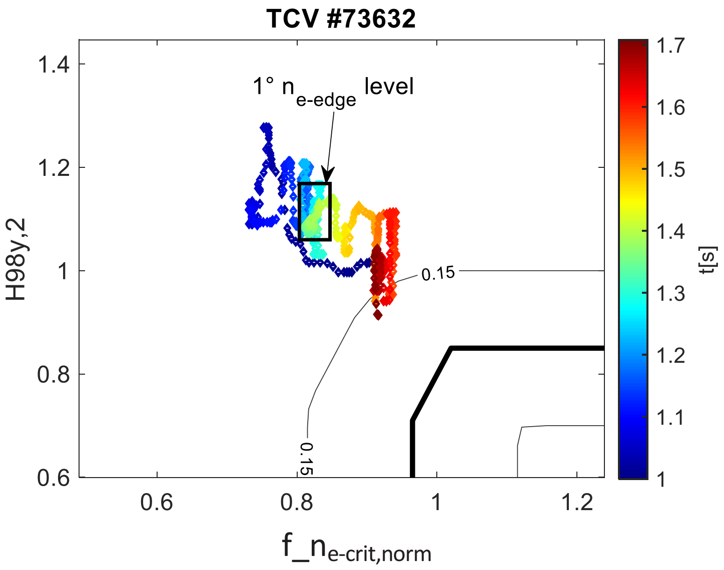


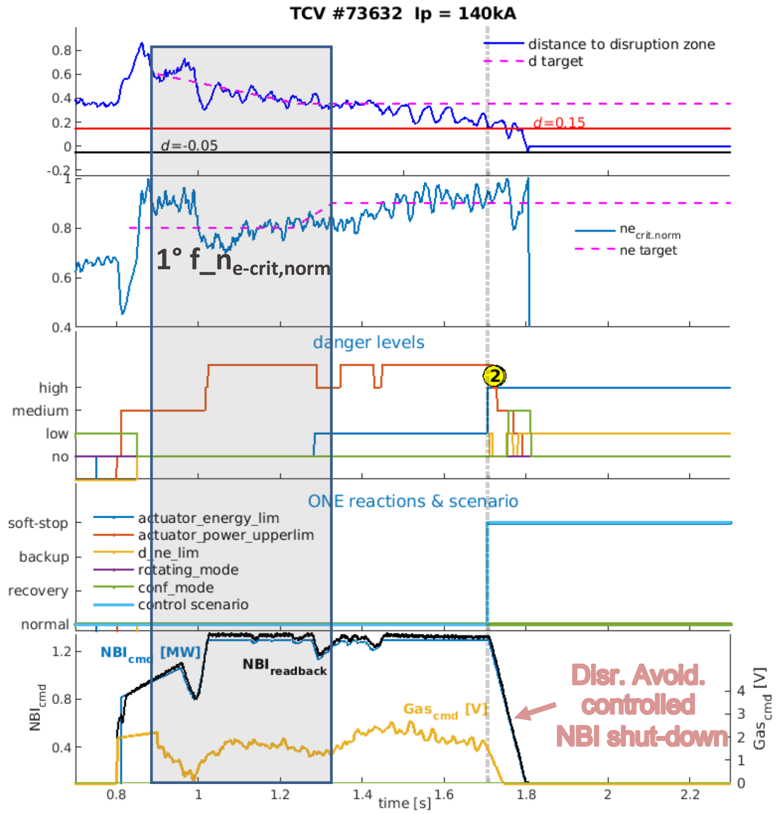
- Demonstration of disruption prevention and avoidance: ‘proximity control’ of distance and edge density close to the H-mode density limit

Swiss Plasma Center

H-mode Density Limit with proximity control on TCV

- Simultaneous **active regulation** on **NBI power** and **gas flux** to track respectively targets on $\mathbf{d_{H98y,2\text{-}f\_n_{e\text{-}crit,norm}}}$ & $\mathbf{f\_n_{e\text{-}crit,norm}}$
- **Proximity control** starts at 0.9s (after entrance into H-mode), progressively decreasing ***d-target*** and keeping $\mathbf{f\_n_{e\text{-}crit,norm}}$ at the level of the left vertical boundary (0.8) corresponding to d=0.15 (for smaller values **DA asynchronous response** takes over)

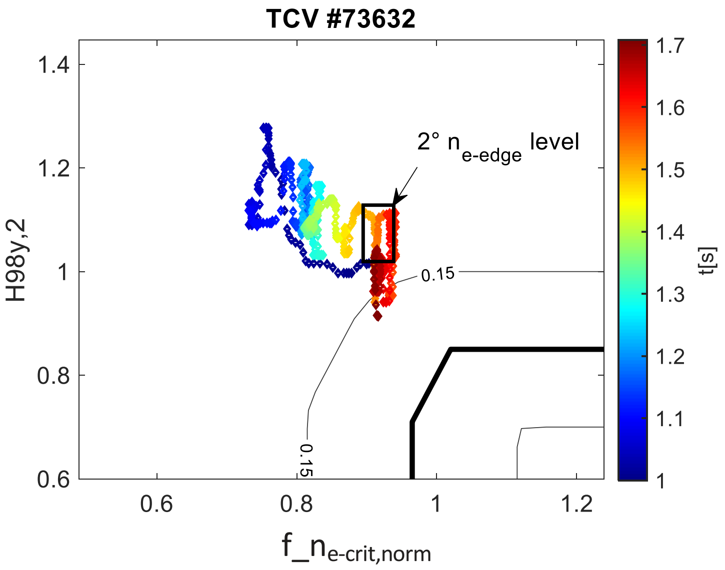


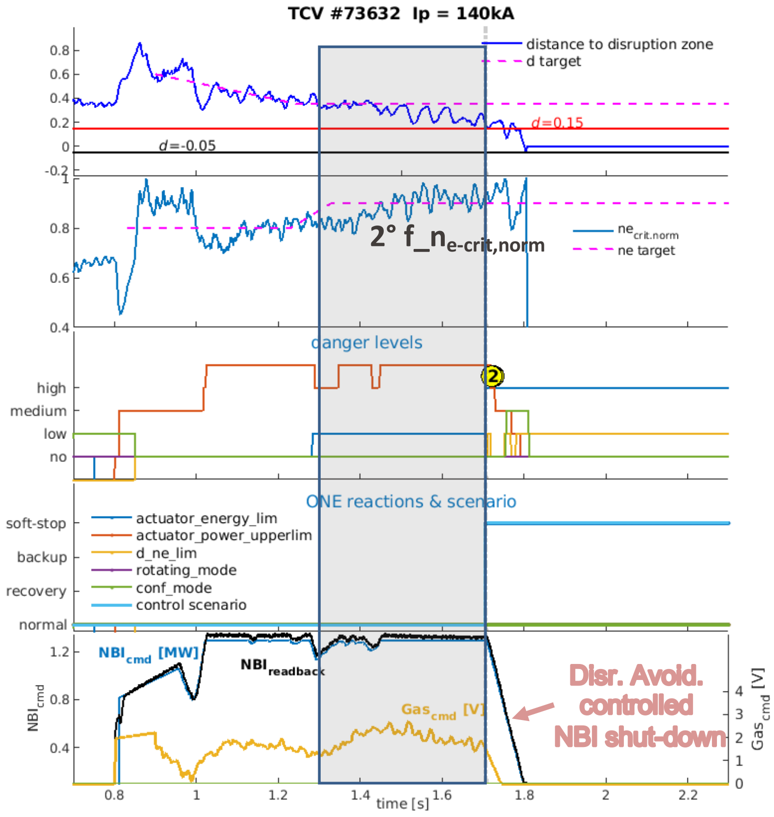


- Demonstration of disruption prevention and avoidance: ‘proximity control’ of distance and edge density close to the H-mode density limit

H-mode Density Limit with proximity control on TCV

- Simultaneous **active regulation** on **NBI power** and **gas flux** to track respectively targets on **$d_{H98y,2\text{-}f\_n_{e\text{-}crit,norm}}$** & **$f\_n_{e\text{-}crit\text{-}norm}$**
- The **2nd phase of proximity control** aims to move the target on **$f\_n_{e\text{-}crit\text{-}norm}$** to 0.9 trying to counteract energy conf. degradation observed when approaching density limit, keeping then stable both **$f\_n_{e\text{-}crit\text{-}norm}$** & **$d_{H98y,2\text{-}f\_n_{e\text{-}crit,norm}}$** (at ~0.4)

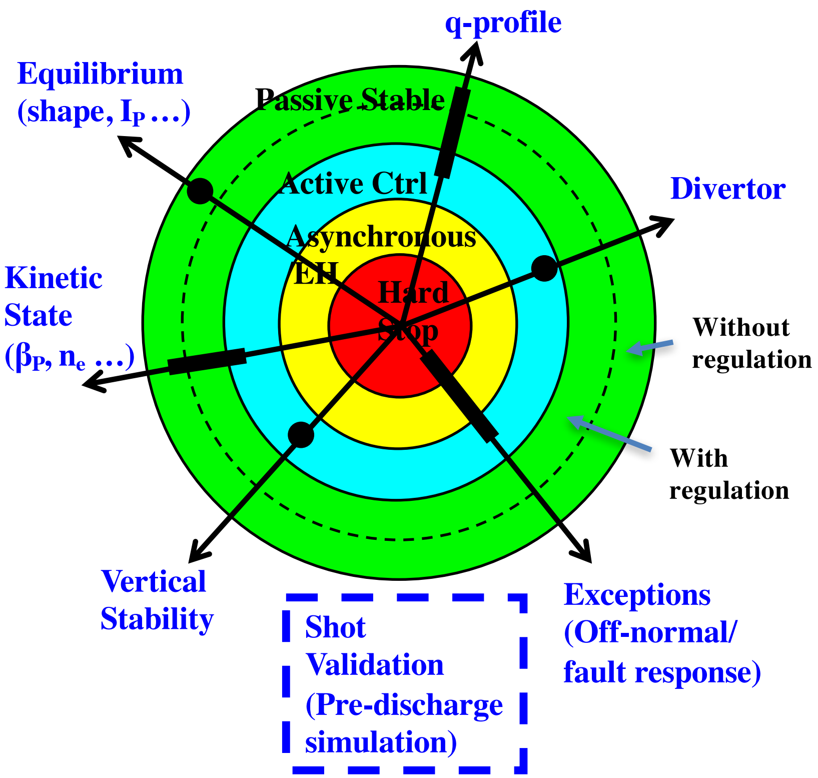




- Demonstration of disruption prevention and avoidance: 'proximity control' of distance and edge density close to the H-mode density limit

Effective Exception Handling for Asynchronous Disruption AVOIDANCE

Control Operating Regime Map



q-profile

Equilibrium (shape, I_P …)

Passive Stable

Active Ctrl

Asynchronous EH

Hard Stop

Divertor

Kinetic State (β_P, n_e …)

Without regulation

With regulation

Vertical Stability

Shot Validation (Pre-discharge simulation)

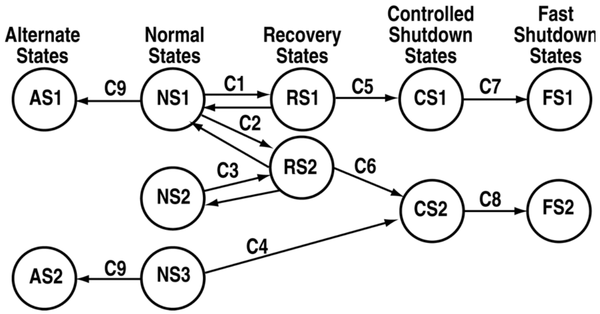
Exceptions (Off-normal/ fault response)

Accomplishment of ITER Control Requires a Sophisticated Exception Handling System

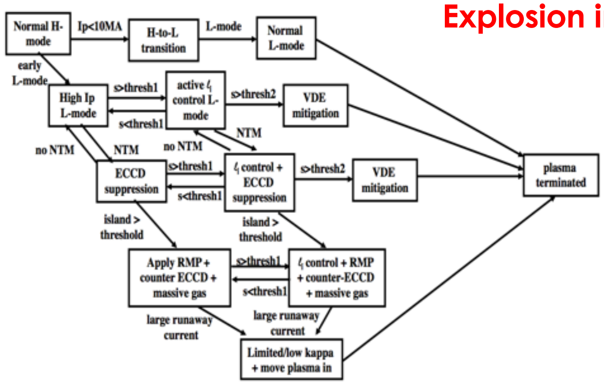
- **Exceptions:**
  - Off-normal event requiring a change in control
  - Prediction by forecasting system
  - Direct detection of exception

- **Exception handling policy includes:**
  - Relevant plasma/system context (e.g. stored energy, saturation state of actuators)
  - Specific signals to be predicted or detected
  - Control modification response to exception: command waveforms, algorithm characteristics…

Exception Handling Will Support a Finite State Machine Architecture



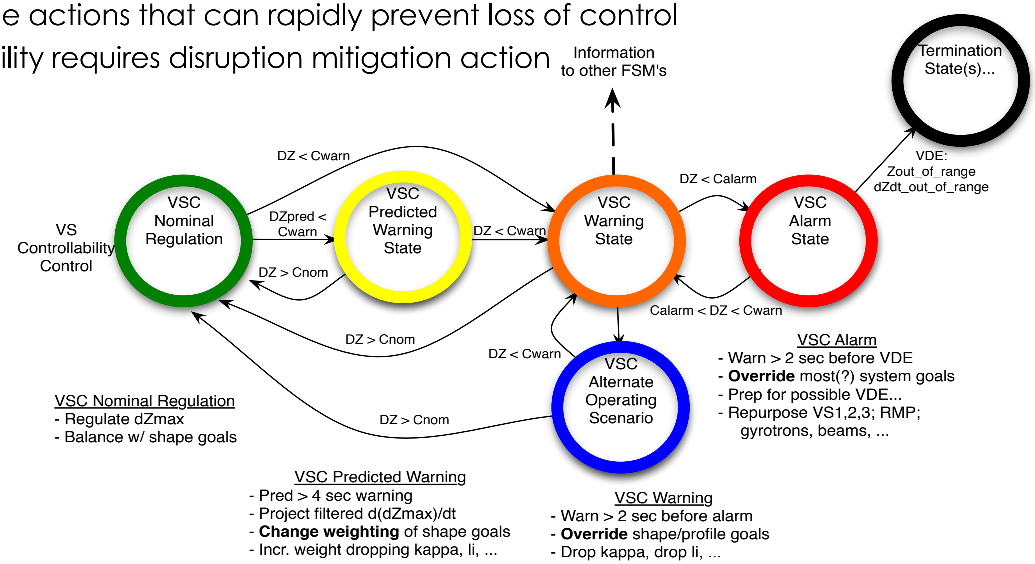
Research is Required to Prevent Explosion in Complexity



Vertical Controllability Exception Handling Exemplifies Broad Class of Finite State Machine Approaches

- **Vertical control exception aspects common to many instabilities:**
  - Accurate metric to quantify proximity to boundary
  - Equilibrium, profile actions that can rapidly prevent loss of control
  - Growth of instability requires disruption mitigation action

- **Finite State Machine Exception Handling architecture:**
  - Enables tracking gradual loss of controllability
  - Responses to nominal, warning, alarm, or termination states
  - Recovery or alternate scenario actions
  - Stability margin m_S proxy for more accurate controllability metrics



VSC Nominal Regulation
- Regulate dZmax
- Balance w/ shape goals

VSC Alarm
- Warn > 2 sec before VDE
- **Override** most(?) system goals
- Prep for possible VDE...
- Repurpose VS1,2,3; RMP; gyrotrons, beams, ...

VSC Predicted Warning
- Pred > 4 sec warning
- Project filtered d(dZmax)/dt
- **Change weighting** of shape goals
- Incr. weight dropping kappa, li, ...

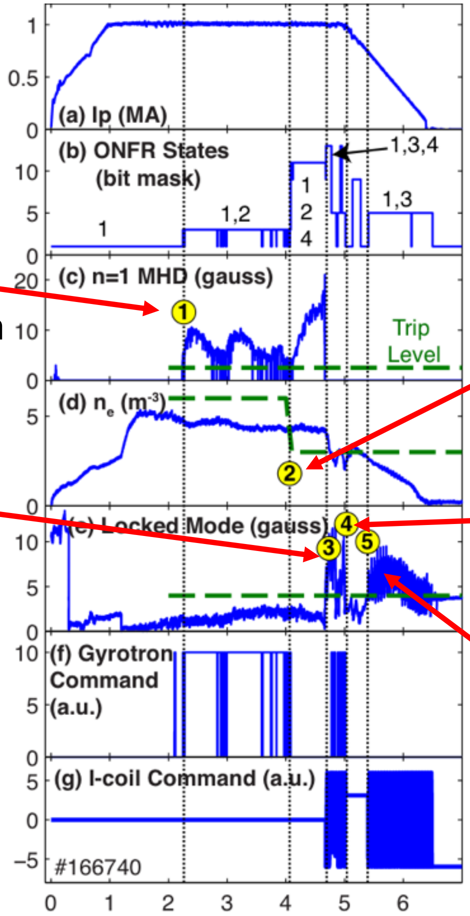
VSC Warning
- Warn > 2 sec before alarm
- **Override** shape/profile goals
- Drop kappa, drop li, ...
- Move plasma to incr. coupling

$$m_S \approx \left[\frac{1.47}{(\kappa - 1.13)} \frac{\left(1 + e^{-2\ell_i + 1}\right)}{2} - 1 \right] \left\{ 1 + 0.60\left(\beta_P - 0.1\right) \right\}$$

Exception Handling Finite State Machines Can Accomplish Sophisticated Response Chains (DIII-D Example)

(1) NTM Detected
→ECCD suppression

(3) Locked mode detected→3D entrainment + synchronous ECCD



(2) High Density trip disables
ECCD temporarily, NTM grows

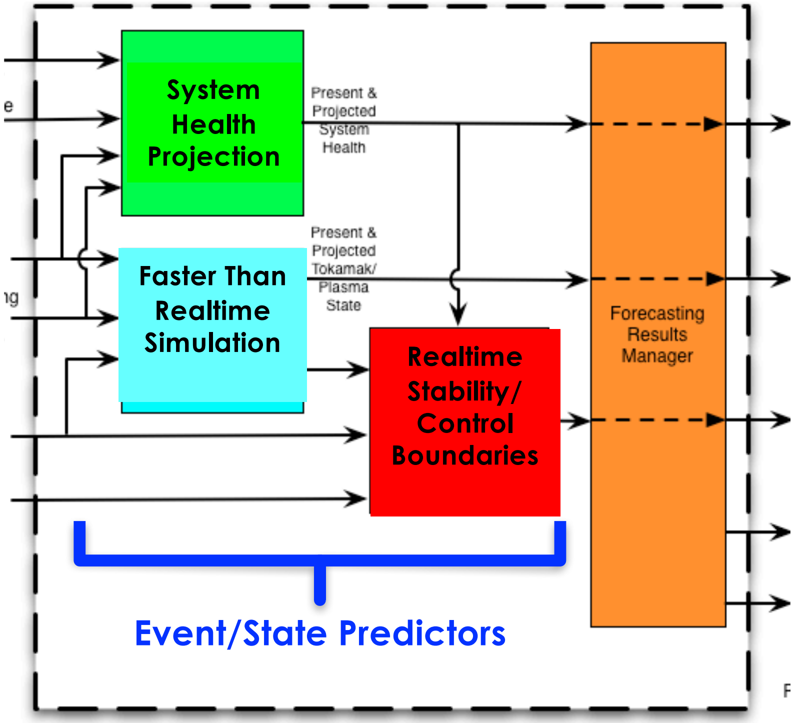
(4) Temporary locked
mode recovery

(5) Successful handling of
new locked mode
through safe rampdown

Exception Handling Systems Require a Powerful Forecasting Capability for Sufficient Look-Ahead

- **Forecasting Inputs:**
  - Machine states
  - Plant system states
  - Pulse schedule
  - Exception handling modified pulse schedule
  - Realtime equilibrium reconstruction data
  - Other diagnostic signals

Forecasting System Functional Block



- **Forecasting Outputs:**
  - Controllability thresholds to inform Exception Handling response
  - Quantified Risk of disruptive state to trigger Disruption Mitigation System

What Roles Must Forecasters/Detectors (of anything) Play in Reactor Operation? How Are They Used?

- **Predict future STATE (plasma or plant system) under present control trajectory**
- **Predict future STABILITY or CONTROLLABILITY (boundary proximities)**
- **Enable control to REGULATE the STATE (e.g. Model Predictive Control)**
- **Enable control to REGULATE PROXIMITY to controllability boundaries**
- **Predict specific exceptions and faults for EXCEPTION HANDLING**
- **Provide specific basis for TRIGGER OF EMERGENCY RESPONSES**
  - Shutdowns: rapid controlled, emergency "uncontrolled"
  - Mitigation action (view as a part of shutdown, but critical action)

What Roles Must Forecasters/Detectors (of anything) Play in Reactor Operation? How Are They Used?

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Predictors Must Support and Enable Control Actions:

- **Continuous Control**
- **Control of Proximities to Boundaries**
- **Exception Handling**
- **Alarms/Emergency Response**

)

- Predict specific exceptions and faults for EXCEPTION HANDLING
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  - Shutdowns: rapid controlled, emergency "uncontrolled"
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Exception Handling and Control is Possible Only If Predictors Are Designed to Provide Information in Actionable Form → Requirement Metrics

1. **Must predict SPECIFIC pre-disruptive phenomena to enable control:**
   - VDE, radiation limit, n≠0 MHD stability/controllability, TM-stability profile state, etc…
   - For PREDICTOR, identify proximity NOT actual mode growth (= detect)
   - Disruptions aren't a thing to predict!!!! They're the end result of many different risky phenomena which must THEMSELVES be predicted individually…

2. **Must provide a CONTINUOUS variable that quantifies proximity (& can GENERATE triggers):**
   - Vertical Controllability metric: e.g. ΔZmax
   - Tearing mode stability metric: Turco J-well depth

3. **Must be REAL-TIME CALCULABLE (control is real-time by definition…)**

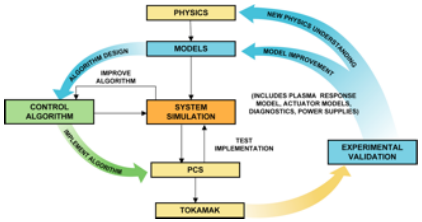
4. **Must be linked to SPECIFIC CONTROL ACTIONS and provide SUFFICIENT LEAD TIME**

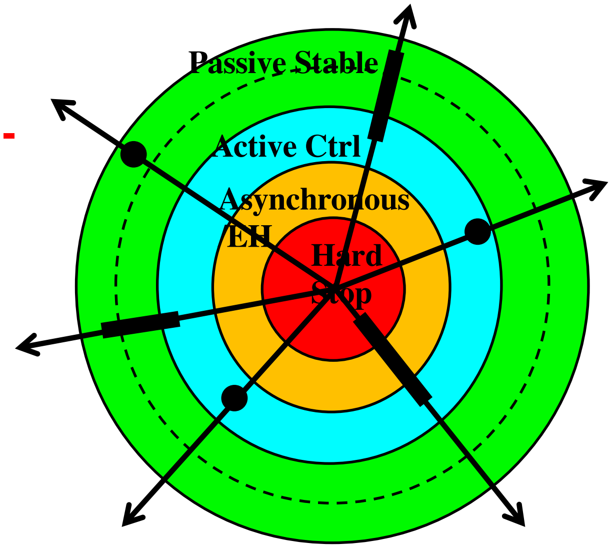
5. **Must be EXTRAPOLABLE to new device (e.g. ITER) control solution PRIOR TO OPERATION:**
   - ITER control requirement: must validate shot prior to execution…
   - COULD allow iterative improvement over time…

Bringing It All Together

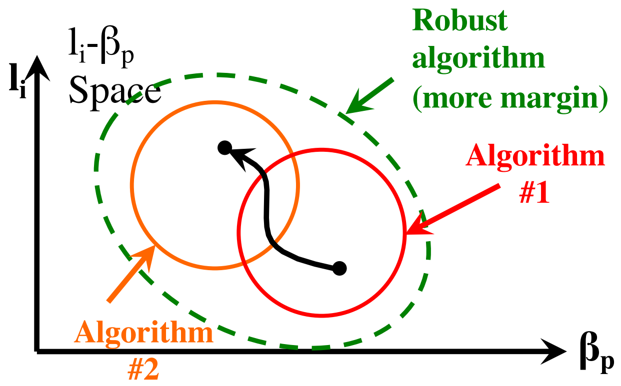
Reducing Disruptivity Toward Zero Can Be Achieved with Specific Scenario and Control Approaches

Systematic controller design with uncertainty-quantified models





Controllers designed for quantifiably robust performance



Verification and validation of performance via simulation

Effective asynchronous Exception Handling for disruption AVOIDANCE

Continuous disruption PREVENTION with proximity control

High Performance, High Reliability Control Can Prevent and Avoid Disruptions in Tokamaks

- **Disruptions are the result of insufficient control capability:**
  - Consequence of design and operational choices
  - Hardware/system faults + human error or human intention

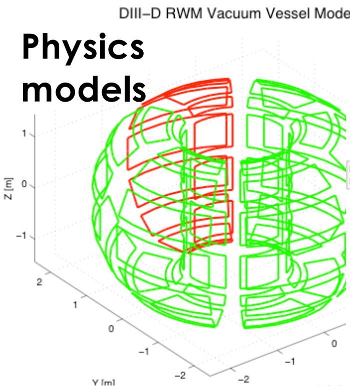
- **High reliability fusion reactors are achievable with validated, high reliability plasma control design:**
  - Disruption prevention through control design based on validated models, performance metrics
  - Verification of implementation and function with simulations
  - Provable exception handling algorithms and response systems for asynchronous disruption avoidance

- **Control design accounting for Control Operating Space is critical to successful tokamak reactors:**
  - Scenario design and operation
  - Active control algorithms
  - Proximity-to-instability regulation
  - Exception handling

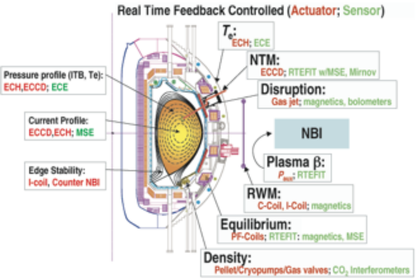
Path to Control of ITER and Operational Fusion Reactors is Rich with Research Opportunities

- **Control physics:**
  - Plasma response models **for control**
  - Heating, current drive effects models
  - Instability physics models
- **Control mathematics:**
  - Integrated multivariable algorithms
  - Robust design methods
  - Design solutions for nonlinearities
  - Provable architectures and algorithms for exception handling
  - Workflows that optimize balance of physics/data-driven design
- **Tool development:**
  - Modeling/simulation/validation/verification
  - Computational solutions: Faster-than-Real-Time simulations

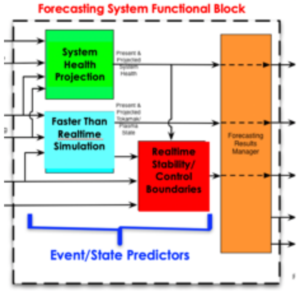
Physics models



High performance experiments



Computational tools



More physics models…